AN EXPERIMENTAL ANALYSIS OF THE DYNAMICS OF A SUBMERGED TETHERED CRADLE IN A SEAWAY

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by

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ABSTRACT

Submerged recovery of small submersibles by means of surface tethered platforms offers the possibility of operations in sea states higher than is now possible using surface recovery means. The Woods Hole Oceanographic Institution's submersible support catamaran LULU has such a tethered system. The system consisting of cradle, chains, and hoist is designed to recover DSRV ALVIN at a depth of 100 feet, and then lift the submersible rapidly through the air-sea interface. Scientific commitments as well as possible damage to the cradle and/or ALVIN, and danger to personnel have prevented full scale recovery experiments. A 1/40 scale model of the catamaran, chain and cradle was constructed to investigate cradle heave and pitch response in regular sinusoidal waves. Model tests were conducted at the Massachusetts Institute of Technology Tow Tank Facility and data was recorded electronically and photographically. Test runs were made at various ship speeds, cradle depths, wave heights, wave lengths, and cradle suspension modifications. Results indicate that for the existing system, cradle pitch and heave is only slightly attenuated over catamaran response at speeds less then 3 knots (full scale). By decreasing the number of cradle suspension points, and varying hoist resiliency and cradle added mass characteristics, cradle motion can be substantially reduced over catamaran motion.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOTATION

H	wave height measured peak to trough
RAO	response amplitude operator
z_o	heave measured positive upward
θ_o	pitch amplitude
h_o	wave height measured peak to trough
λ	wave length measured peak to peak
ω_e	frequency of encounter
u_w	wave velocity
u_s	ship speed
α	heading direction of vehicle relative to the direction of wave propagation ($\alpha = 180°$ for head seas)
C_d	coefficient of viscous drag
ϕ	wave velocity potential
g	acceleration due to gravity
A	one half peak to trough wave height
ω	wave frequency
K	wave number
k_o	values of K which satisfy $k_o \tanh k_o h = K = \omega^2/g$
h	water depth
t	time
δ	wave phase angle
z	depth measured negative downward from the free surface
u	velocity component in x direction
w	velocity component in z direction
M	real cradle mass plus added mass $(m + m_a)$
C	damping coefficient of cradle

C_c	critical damping
k	equivalent spring constant
X_o	amplitude of ship vertical motion
y	cradle vertical motion (+ upward)
y_o	amplitude of platform vertical motion
A_c	projected area of cradle normal to flow
ρ	fluid density
ω_n	undamped natural frequency, $\omega_n = (k/M)^{\frac{1}{2}}$
X_{STAT}	at rest spring deflection due to suspended mass
$S_\zeta(\omega)$	spectral density, such that total energy in an increment $\delta\omega$ at the central frequency ω_n is $\rho g[S_\zeta(\omega_n)\delta\omega]$
L	ship length

INTRODUCTION

The Deep Submergence Research Vehicle (DSRV) ALVIN and her support catamaran LULU are perhaps the most successful deep submersible combination that regularly operates in the open ocean. Funded and owned by the U.S. Navy and operated by the Woods Hole Oceanographic Institution, ALVIN has to date completed 390 dives in six operating seasons from 1964 to 1971. The most recent operating period, lasting from 4 June 1971 to 17 December 1971, was ALVIN's most active with a total of 82 dives.

As presently configured (Figure 1), LULU has a 30 ton net capacity cradle with four-point chain hoists located between her two hulls just aft of mid-ships. During transit, the cradle is two-blocked in the raised position such that the top of the cradle is flush with the surrounding deck, providing easy access for maintainence of ALVIN. Launch of the submersible is executed by having the catamaran lie to with the sea astern, while the cradle is lowered so that it is clear of the floating submersible. Snubber lines prevent lateral relative motion between ALVIN and LULU until the pilot on board ALVIN has powered her clear of LULU's stern at which time all lines are removed, and the dive can commence. Retrieval is the reverse of the launch sequence. Upon completion of the dive, ALVIN surfaces well clear of LULU. The two vessels then close each other with the aid of visual and/or radio direction devices. The catamaran maneuvers such that the seas are astern (Figure 2), at which time ALVIN approaches LULU, receives snubber lines, drives herself between the hulls, and is positioned over the submerged cradle. When alignment is correct, the cradle

Figure 1. DSRVT LULU Underway with DSRV TURTLE.

Figure 2. ALVIN Maneuvering into Surface Recovery Position.

is raised with ALVIN aboard at a rate of 30 feet per minute, until the combination is well clear of the air-sea interface, and secured to the catamaran's deck.

It is this unique combination of catamaran, cradle, and manned submersible, which has enabled launch and retrieval consistently up to sea state 3, with rare instances of recovery in sea state 4 necessitated by unexpected weather changes during the period of a dive. The single greatest unscheduled factor in dive cancellations is weather. Of the 196 days of operation in 1971, 27 were lost due to unsatisfactory weather conditions. As Mavor (1971) states, depending upon ship location and forecast or actual weather on station, one of the following reasons for dive cancellation will result:

Weather Forecast:
1) hurricane/full gale - cancels or postpones cruise
2) sea state 4 - cancels dive on station
3) gale - aborts cruise on station

Weather on Station:
1) sea state 4 - aborts/postpones dive
2) large storm - may abort cruise
3) fog - aborts/postpones dive

In particular, Mavor cites a recurring cause for dive cancellation in the North Atlantic off Cape Cod as an increase from sea state 3 to 4 on days when the prevailing southwest wind increases from 10 knots in the morning to 20 knots in the afternoon. Figure 3 is included to assist the reader in better understanding the magnitude of state 4 sea in relation to a 15 ton, 23 foot long vehicle. Table I and Figure 4 quantitatively define characteristics

Figure 3. ALVIN in a State 4 Sea.

Table I. Characteristics of Fully Arisen Sea.
(After W. Marks, Geo-Marine Technology Nov. 1964).

Sea State	Wind Vel. (kts)	Wave Height (ft.) Mean	Sig. $H^{1/3}$	$H^{1/10}$	Period (sec) Max. Energy	Mean	Length (ft) Average
1	4-7	.18-.6	.29-1	.37-1.2	2-3.4	1.4-2.4	6.7-20
2	7-14	.88-1.8	1.4 -2.9	1.8 -3.7	4-5.4	2.9-3.9	27.0-52
3	14-16	2.0 -2.9	3.3 -4.6	4.2 -5.8	5.6-6.5	4.0-4.6	59.0-71
4	17-20	3.8 -4.3	6.1 -6.9	7.8 -8.7	7.2-7.7	5.1-5.4	90.0-99
5	20-23	5.0 -7.9	8.0 -12	13.0 -16	8.1-9.7	5.7-6.8	111.0-160
6	24-30	8.2 -11	13.0 -18	17.0 -23	9.9-11.3	7.0-7.9	164.0-212

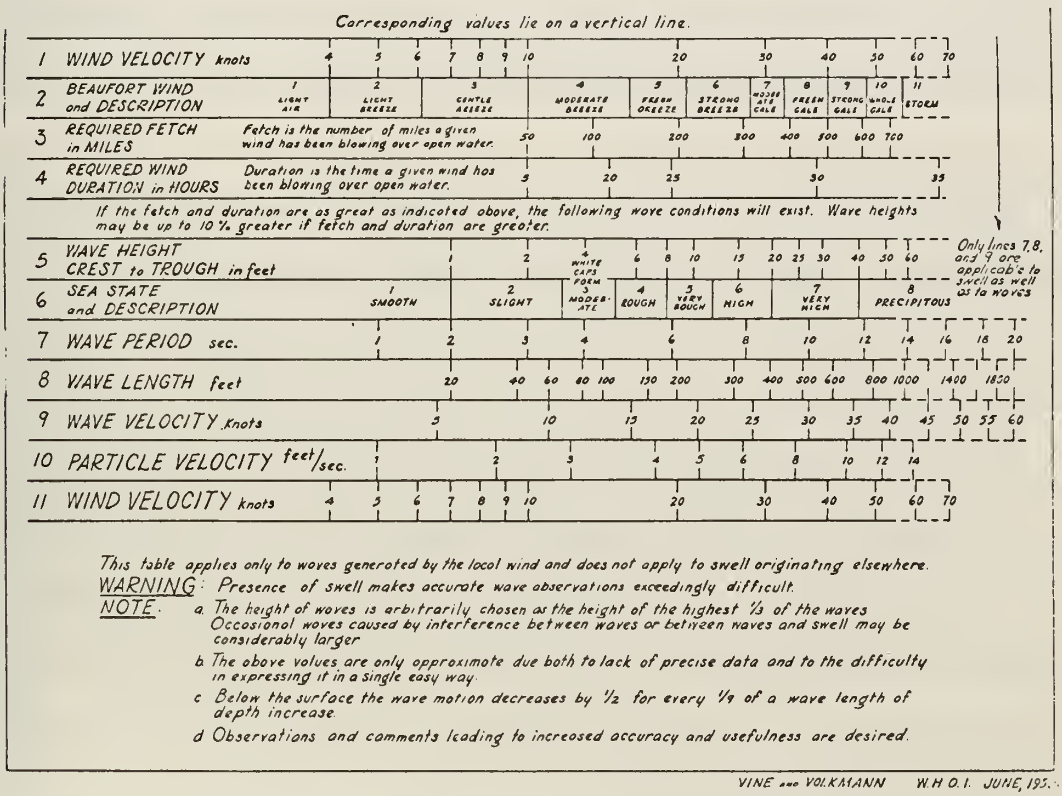


Figure 4. Summary of Wind Wave Characteristics.
(Reproduced from Vine and Volkman 1950).

of a fully arisen wind driven sea. Average sea state statistics for the North Atlantic according to Wiegel (1964), show that for the months of May, June, and July, sea states 1 thru 3 will occur 25 per cent of the time, while a sea state of 4 thru 4 1/2 (wave height 5-10 feet) will occur 37 per cent of the time. For the months of August, September, and October, sea states 1 thru 3 have only a 7 per cent occurrence, while state 4 thru 4 1/2 seas occur 36 per cent of the time. It is obvious then, that a capability to consistently recover ALVIN in state 4 seas would substantially decrease the number of dives cancelled due to weather.

Since the consistent recovery of ALVIN in a state 4 sea by the means already described would be difficult at best, and certainly dangerous to equipment and personnel, an alternate approach to recovery is seriously being considered. In 1969, anticipating the arrival of DSRV SEA CLIFF, LULU was extensively modified. In addition to a new bow (Figure 5), increased deck space for crew and equipment, increased displacement via added double hulls on each pontoon, and a new cradle to handle the 25 ton submersible, a four point chain hoist system was installed. Four 120 feet long lengths of 6 inch chain links over four synchronized wildcats form the hoist system for the cradle (Figure 6). This capability to lower the cradle to a depth of 100 feet, where surface wave action is significantly attenuated, offers the possibility of submerged mating of ALVIN to the cradle in seas higher than sea state 3. Once docking is accomplished, a rapid transit through the air/sea interface would avoid dangerous relative motion between the catamaran and cradle.

A

B

Figure 5. Bow View of DSRVT LULU a) Before Alteration and, b) After Alteration.

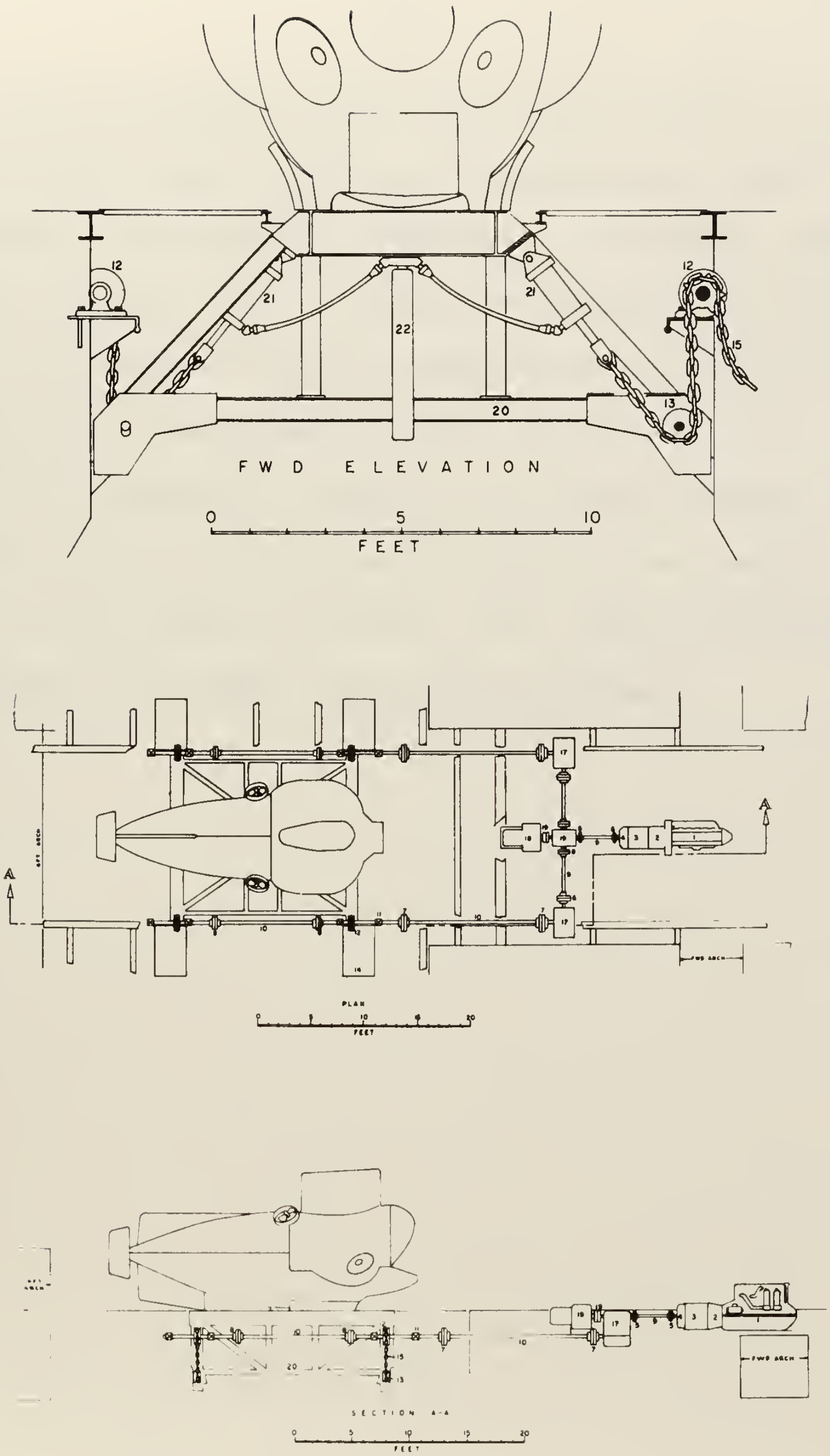


Figure 6. LULU Lift Cradle and Hoist for ALVIN Recovery
a) Forward Elevation, b) Plan View, and c)
Side Elevation. (Reproduced from Aldrich 1971).

Full scale system testing without prior analysis and motion prediction would require elaborate instrumentation, valuable time diverted from scientific commitments, and possible damage to ALVIN, LULU, the cradle and danger to personnel. For this reason it was proposed that scale model tests be conducted before full scale trials and/or modification. The following then is a report of the preparation, execution, and results of model tests conducted using a 1/40 scale model of LULU with her cradle suspended at a scale depth of 100 feet, over a range of ship speeds, wave heights, wave lengths, and system alterations.

THEORY

Much study has been given to the dynamics of a submerged tethered cradle acted upon by ship motion and wave force. Vandiver (1969) and Heller and Motherway (1971) have extensively analyzed such systems in terms of discrete spring-mass-viscous damped configurations. Kenny (1969) repeated much of Vandiver's work, with additional effort directed toward a physical model to verify theoretical calculations. To my knowledge, the only similar experimental work was carried on by the Naval Ship Research and Development Center, where the new catamaran ASR and Deep Submergence Rescue Vehicle (DSRV) retrieval cradle and hoist were evaluated.

This thesis is primarily an experimental analysis which compliments the above studies. Theoretical analysis is limited to that necessary to justify assumptions made in modeling, validity of experimental data, and as a guide to the alterations necessary for acceptable performance of the cradle in state 4 seas.

The first area of interest is LULU's response amplitude operator (RAO), since the direct driving force producing cradle motion is the heave and pitch of the catamaran. The RAO is defined as the magnitude of response (measured from the calm water position) of heave (z_o) and pitch (θ_o) over a series of wave lengths for a given ship speed non-dimensionalized by wave height (h_o) and wave slope ($2\pi h_o/\lambda$) respectively. If the response of a ship is in fact linear, then for a given frequency of encounter (ω_e), where:

$$\omega_e = \frac{2\pi}{\lambda}(u_w - u_s \cos \alpha) \qquad (1)$$

λ = wave length

$u_w = (\frac{g\lambda}{2\pi})^{\frac{1}{2}}$ = wave velocity

u_s = ship speed

α = heading direction of vehicle relative to the direction of wave propagation ($\alpha = 180°$ for head seas)

the ratio Z_o/h_o and $\theta_o/(2\pi h_o/\lambda)$ will remain constant as wave height is varied.

Such response operators may be derived from model tests, or more recently, from computer programs using "strip theory" as described in Korvin-Kroukovsky (1961). Booth (1967) conducted model tests on 1/20 scale models of LULU and ALVIN. The models were positioned in the surface recovery position, with ALVIN between the catamaran hulls at zero speed, encountering head seas of height 1.25 and 2.5 feet (full scale). Response of these vehicles was also calculated using the M.I.T. ship motion computer program. The results of these two approaches for LULU are included (Figure 7). Tow tank tests on my 1/40 scale model equivalent to Booth's showed excellent agreement in heave and pitch with the theoretical and experimental results displayed in Figure 7.

Froude scaling was applied to the cradle as well as the catamaran, since the coefficient of viscous drag (C_d) is nearly independent of Reynolds number for sharp edged objects such as the plates and girders which make up the horizontal cross-section of the recovery cradle. The full scale recovery system consists of LULU, the cradle, and four 120 foot lengths of one inch chain.

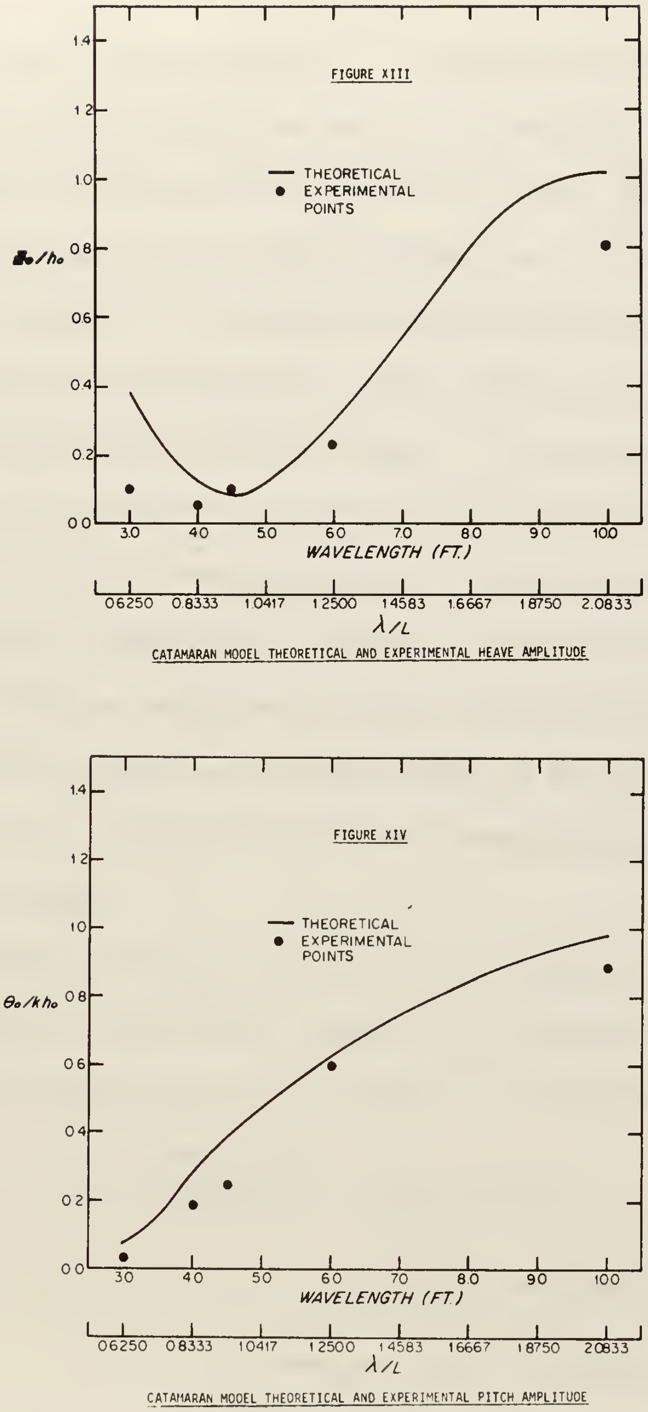


Figure 7. Catamaran Model Theoretical and Experimental Response Characteristics in a) Heave, and b) Pitch. (Reproduced from Booth 1967)

The chain has a spring constant of 18 tons/inch, and four chains yield an equivalent spring constant of 72 tons/inch. With a combined weight for the cradle and ALVIN of 30 tons, the static elongation of the chain is less than .5 inches over 100 feet. The system was assumed to be inelastic for modeling purposes.

The chain which links the surface vessel and submerged platform can transmit only a tensile force. It was hypothesized that the cradle would follow the upward motion of the catamaran, while falling freely during downward motion. Since the chain is attached at two different longitudinal stations on the catamaran aft of mid-ships, different magnitudes of heave excitation should be expected on the leading and trailing edges of the cradle. This is to say that a coupled pitch and heave motion of the cradle should be observed.

A secondary forcing function is water particle motion caused by a progressive wave system. Newman (1971) defines a velocity potential for waves moving in the positive X-direction as:

$$\phi = \frac{gA}{\omega} \frac{\cosh k_o(Z+h)}{\cosh k_o h} \cos(k_o x - \omega t + \delta) \tag{2}$$

where k_o = values of k which satisfy $k \tanh kh = K = \frac{\omega^2}{g}$

Z = is measured negative downward from the free surface

A = 1/2 peak to trough wave height

h = depth of water

δ = arbitrary phase angle

The orbital motions of individual fluid particles in their wave

system separated into horizontal and vertical components are:

$$u = \frac{d\phi}{dx} = -\frac{gA}{\omega} k_o \frac{\cosh k_o(Z+h)}{\cosh k_o h} \sin(k_o x-\omega t+\delta) \qquad (3)$$

$$w = \frac{d\phi}{dz} = -\frac{gA}{\omega} k_o \frac{\sinh k_o(Z+h)}{\cosh k_o h} \cos(k_o x-\omega t+\delta) \qquad (4)$$

These two velocity components are 90° out of phase, and as $Z \to -\infty$ these relations become equal such that water particles move in circular orbits of radius Ae^{KZ} where A is one half the peak to trough wave height, and $K = \omega^2/g$. The radius decreases exponentially with depth, such that at depths greater than half a wave length ($e^{KZ} = e^{-\pi} = .04$), no significant particle motion occurs. If the depth of water is not infinite, but relatively shallow ($h < \lambda/2$), the particle orbits become more and more elliptical, until in the limit, motion is purely horizontal. Water particle motion is not a significant excitation force acting on the cradle for this study because, the cradle is suspended at 100 feet and wave lengths in excess of 200 feet occur predominantly in sea states greater than sea state 5 (see Figure 4).

The simplest modification to the cradle/hoist system which would decouple catamaran pitch from the cradle would be reducing the number of cables from two forward and two aft, to two centered on the port and starboard sides of the cradle. Although this eliminates cradle pitch, it does not decouple heave. The effect of such an alteration on the influence of ALVIN, cradle lift, or air/sea interface characteristics must be the subject of further investigation. It should be noted, that my study deals with the

cradle suspended at a depth of 100 feet below LULU without ALVIN attached or in near proximity.

The next modification investigated is the effect of changing different parameters on a damped, spring/mass system. Heller and Motherway (1971) offer the following model for such a system. Figure 8 represents a schematic of the catamaran, chain, and cradle system. If this analysis is to yield insight into attractive system modifications, the chain (or other hoist mechanism) must be assumed to be elastic.

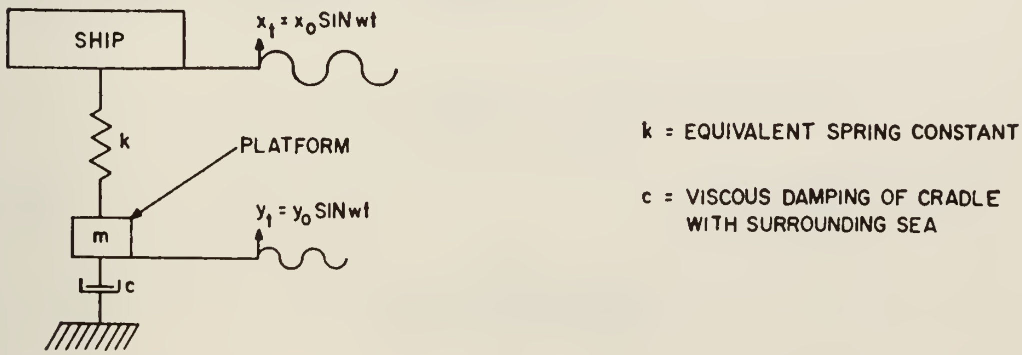


Figure 8 Schematic Catamaran-Chain-Cradle System

The differential equation for this system is:

$$M\ddot{y} + C\dot{y} + ky = kX_o \sin \omega t \qquad (5)$$

where

C is the damping coefficient of the cradle

k is the equivalent spring constant of the connecting line

M is the mass of the cradle plus its added mass $(m + m_a)$

X_o is the amplitude of ship vertical motion

y is cradle vertical motion (+ upward)

Based on the assumption of small vertical velocity of the

cradle, a linear approximation for the damping yields:

$$C = \frac{4\rho A_c C_d Y_o \omega}{3\pi} \tag{6}$$

where

A_c is the projected area of the cradle normal to the flow

C_d is the coefficient of viscous drag

Y_o is the amplitude of the platform verticle motion

The standard solution of Equation (5) is:

$$y = \frac{kX_o \sin \omega t}{[(k-M\omega^2)^2+(C\omega)^2]^{\frac{1}{2}}} \tag{7}$$

or

$$y_o = \frac{kX_o}{[(k-M\omega^2)^2+(C\omega)^2]^{\frac{1}{2}}} \tag{7a}$$

Applying the relation for undamped natural frequency of a single degree of freedom system:

$$\omega_n = (k/M)^{\frac{1}{2}} \tag{8}$$

Equation (7a) may be simplified to:

$$y_o = \frac{X_o}{\{[1-(\frac{\omega}{\omega_n})^2]^2+(\frac{C}{M\omega_n})^2(\frac{\omega}{\omega_n})^2\}^{\frac{1}{2}}} \tag{7b}$$

Substituting Equation (6) into Equation (7b) and performing additional algebraic manipulation results in the following:

$$\left(\frac{4\rho A_c C_d}{3\pi M}\right)\left(\frac{\omega}{\omega_n}\right)^4 y_o^{\,4}+[1-(\frac{\omega}{\omega_n})^2]^2 y_o^{\,2}-X_o^{\,2} = 0 \tag{9}$$

The typical solutions to Equation (9) are represented in Figure 9. The important trend to note is that: (1) in all damping situations, where the system is excited above two times the undamped natural

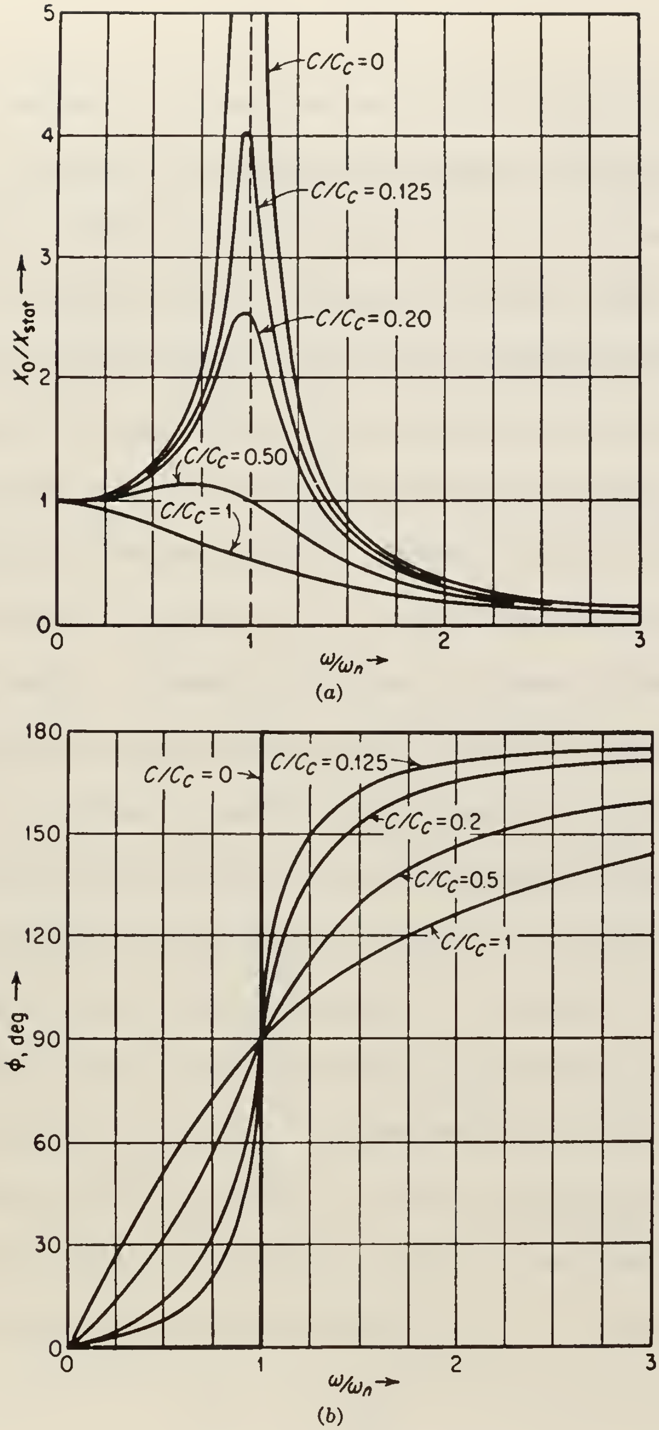


Figure 9. Single Degree of Freedom a) Forced Vibration Amplitude, and b) Phase Angle Between Force and Displacement. (Reproduced from Den Hartog (1956).

frequency, response is less than one half the input; and (2) at such high frequencies, the phase difference in ship/cradle motion is in excess of 130°. Simply then, if two conditions can be met in the just described single degree of freedom system, cradle motion can be significantly reduced over catamaran heave. First, by increasing the resiliency of the hoist system (decrease the spring constant) and increasing the added mass of the cradle, the undamped natural frequency can be lowered to such a point that catamaran motion is sensed only as high frequency noise by the stabilized cradle. Secondly, because the phase difference is so great between ship and cradle motion, the hoist system must have sufficient resiliency to permit elongation of 10 per cent in sea state 4, thereby accounting for the difference in motion. Figure 10 shows sea spectra for sea states 4 and above. Based on this figure, if the cradle system can be designed for a natural frequency of ω_n = .2 rad./sec., then cradle heave will be less than one half catamaran heave for $\omega/\omega_n > 2$. Assume the full scale cradle has a mass of 508 slugs (see Table II) and a flat plate across the bottom of the cradle of equal mass gives it an added mass of 7175 slugs, the spring constant necessary for ω_n = .2 rad./sec. is:

$$\begin{aligned}
\omega_n &= (k/M)^{\frac{1}{2}} \\
k &= \omega_n^{\,2}M \\
&= (.2)^2(508 + 508 + 7175) \\
&= (.04)(8191) \\
k &= 328 \text{ lbs./ft.}
\end{aligned}$$

With a combined cradle/plate weight of 32,556 pounds, this would mean a static spring hoist deflection of 100 feet. Obviously

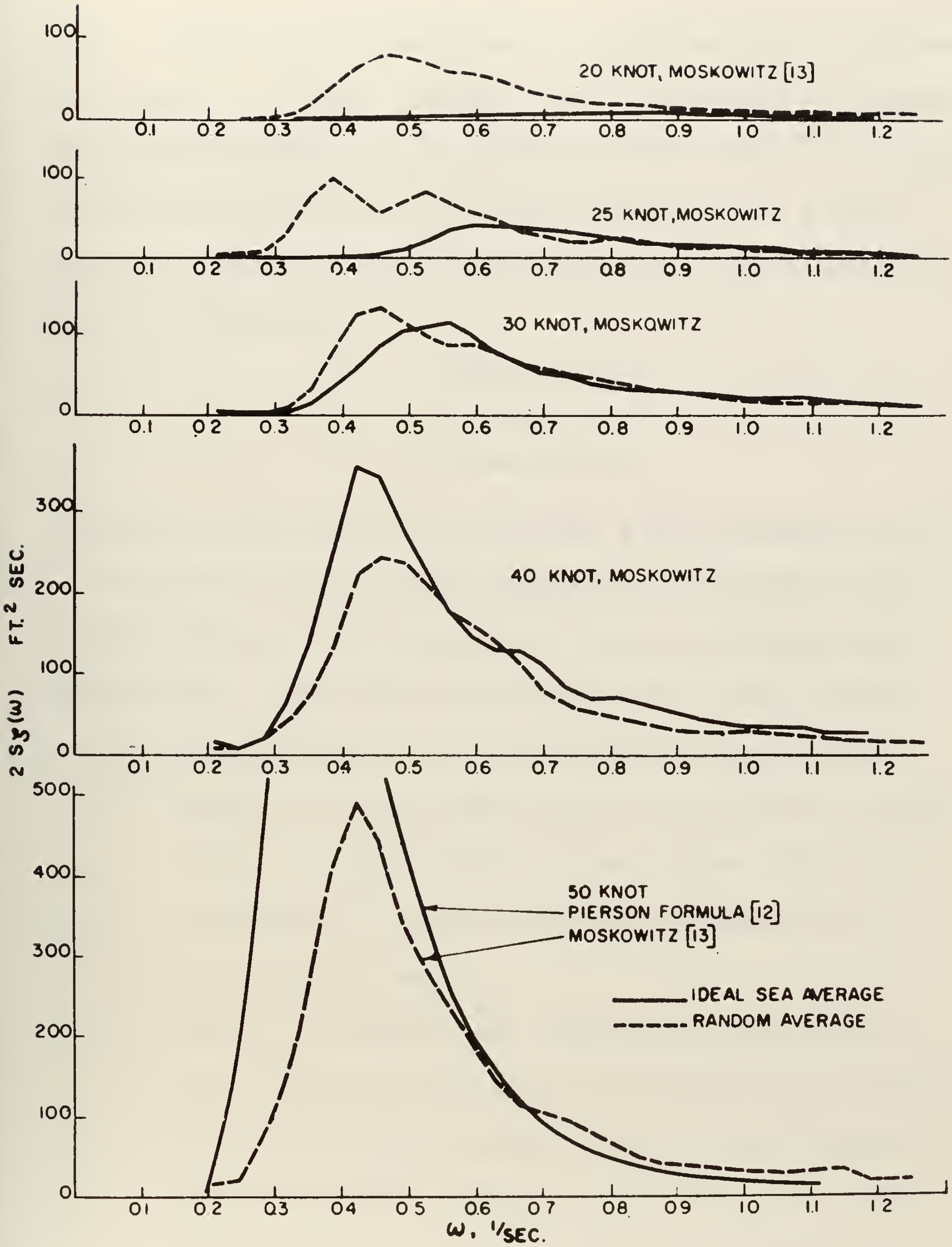


Figure 10. Comparison of Moskowitz Family of Sea Spectra Obtained by Random Sampling with Family of Ideal Average Spectra. (Reproduced from Comstock and Lewis 1968).

this is impractical and unacceptable in a system which is designed for a depth of 100 feet. Without increasing the natural frequency, hence cradle response, if the cradle mass were halved to 254 slugs, and the same added mass of 7175 slugs was provided by a light parachute drogue (6 slugs) hung from the cradle, the spring constant now required is:

$$\begin{aligned} k &= (.04)(254 + 7175) \\ &= (.04)(7429) \\ k &= 297 \text{ pounds/foot} \end{aligned}$$

The static cradle deflection is 28 feet, a more reasonable value.

The above exercise was designed to give the reader a feel for the problems involved in a passive design to decouple ship cradle motion. I feel that improvements in the overall system can be accomplished by one or a combination of several means:

1) Reduction of the in-water weight of the cradle to reduce static spring deflection to under 10 feet. This can be accomplished by means of cradle design having only a slight negative buoyancy.

2) Maximize the hydrodynamic added mass of the cradle by either dynamic thrusters which are acceleration sensitive; a venetian blind type plate, which would offer minimum drag during cradle hoisting, while offering flat plate added mass characteristics during mating; detachable parachute hung beneath the cradle to be jettisoned upon ALVIN/cradle mating; or a combination of the above.

3) A small but simple improvement proposed which does not require an alteration of the existing system is having

LULU make headway, such that a catenary forms in the four hoist chains. This catenary is translated into an equivalent spring, since ship motion at the top of the chain is attenuated in part by the cable straightening as the tension in the line is increased overcoming in part the effects of hydrodynamic drag.

The areas of investigation in this thesis are therefore:

1) Response of the unaltered ship/chain/cradle system with no way on.
2) Effects of forward speed on the response of the cradle
3) Effects of changes in spring and added mass characteristics
4) Effects of suspension alteration from four point to two point suspension on cradle response.

The following section will describe how these experiments were accomplished.

FABRICATION AND PROCEDURE

Model construction and test procedures were designed to be compatible with the M.I.T. Tow Tank Testing Facility which was the most convenient and available facility for the series of experiments. The tow tank is 108 feet long, 9 feet wide, and 4 feet deep, with 26 feet of glass along its outer wall. At one end it has a hydraulically driven metal plate wavemaker hinged at the bottom of the tank. Plate motion is controlled either by an electrical oscillator for making regular sinusoidal waves, or by a tape deck for generation of preprogrammed random seas. Wave amplitude is controlled by the stroke of the wave maker. At the opposite end of the tank is a beach consisting of bailed metal filings which act to dissipate wave energy with minimum reflection. Models are propelled via an overhead carriage which is driven at constant speed by means of a continuous steel tape. The model is attached to the carriage through a combination heave rod/pitch bearing assembly. The heave rod floats in air bearings to minimize system friction. Model pitch and heave are recorded electrically on strip chart paper from outputs provided by a rotary variable differential transformer on the pitch bearing, and a linear differential transformer on the heave rod assembly respectively. Waveheight is measured by means of a two-wire resistance probe and recorded on the same strip chart.

Given the depth of the tow tank as 48 inches, and the requirement to test the cradle at a scale depth of 100 feet below the surface, model scale was set at 1/40 full scale size. This placed the cradle at a depth of 30 inches in the tank, leaving 18 inches

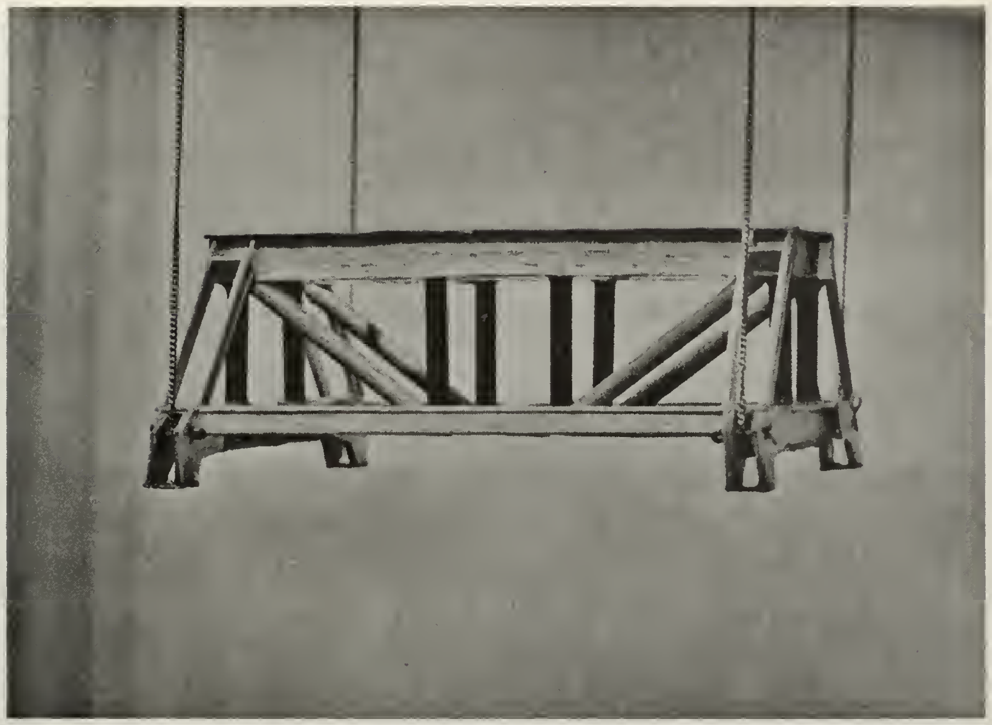
clearance above the bottom to avoid hydrodynamic interference. Kenny (1969) provided half size drawings of a 1/20 scale model of LULU, which were used directly as templates for my model. Carl S. Albro, a fellow student in the joint MIT-WHOI Ocean Engineering Program constructed a very accurate 1/40 scale model of the cradle. Jewlers chain was obtained which scaled the full scale chain in both gross dimension and mass distribution. (Figures 11, 12, and 13) A summary of full scale and model characteristics is listed in Table II. (See Appendix A for determination of radius of gyration.

Table II

Full Scale and Model Characteristics
1/40 Scale

	ITEM	FULL SCALE	MODEL
CATAMARAN	Length, L (ft.)	96	2.4
	Beam overall (ft.)	48	1.2
	Beam, each hull (ft.)	14	.35
	Displacement (lg. ton/lbs)	437	15.3 (includes heave rod/pitch brg.)
	Long. C.G. aft of F.P. (ft)	48	1.2
	Long. Rad. of Gyration (ft)	28.9	.72
CRADLE	Length, L (ft)	17.5	.4375
	Width (ft)	16.3	.4083
	Weight (Dry) (Lg.ton/lbs)	7.3	.2555
CHAIN	Length, L (ft)	100	2.5
	Width, (in)	4	.1
	Weight (Dry) (lbs)	1000	.0156

Figure 11. 1/40 Scale Model of DSRVT LULU and Cradle
(shown unpainted).



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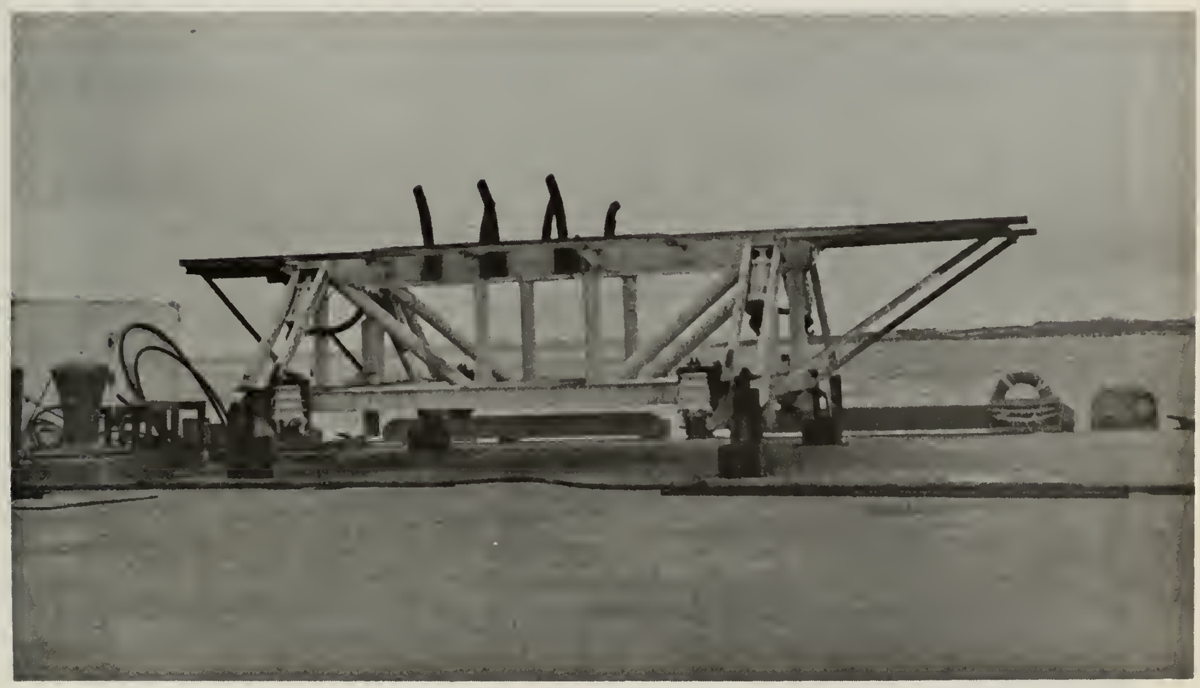


B

Figure 12. Recovery Cradle a) Model with Scale Chain, and b) Full Scale with Surface Support Structure.

Figure 13. Model Cradle Suspended 30 Inches Beneath Catamaran via Four-Point Chain Suspension.

Whereas wave height and catamaran motion could be easily recorded on strip chart paper, the small weight of the cradle (116 grams) made any addition of motion sensing or recording instrumentation highly undesirable since it would significantly alter the dynamic characteristics of the cradle. An acceptable alternative to direct instrumentation was photographic recording of cradle motion, synchronized to catamaran records by including a watch in the field of view of the motion picture camera. As the sweep second hand passed the 5 second mark, an observer would close a hand-held switch making a mark on the strip chart. This time base correlation is critical to phase and relative motion analysis. In order to assure correct length scale during later projection and data reduction, a steel tape measure scale was included directly below the cradle, where it also served as a visual baseline from which to measure cradle heave. This steel measure was attached to the tow carriage with a steel rod so that it was unaffected by wave motion. (Figure 14)

Experiments were conducted with the model stationary and moving, so that the camera had to be able to follow the action. An aluminum frame consisting of 3/4 inch 6061 pipe joined with detachable Nu-Rail fittings was constructed, and attached to the carriage with pipe clamps, (Figure 15). This setup proved quite satisfactory as it was easily assembled and disassembled, providing the necessary range of adjustable members. Additionally, it was easy to transport in a passenger car between Woods Hole and M.I.T., and did not require alteration of the tow tank carriage

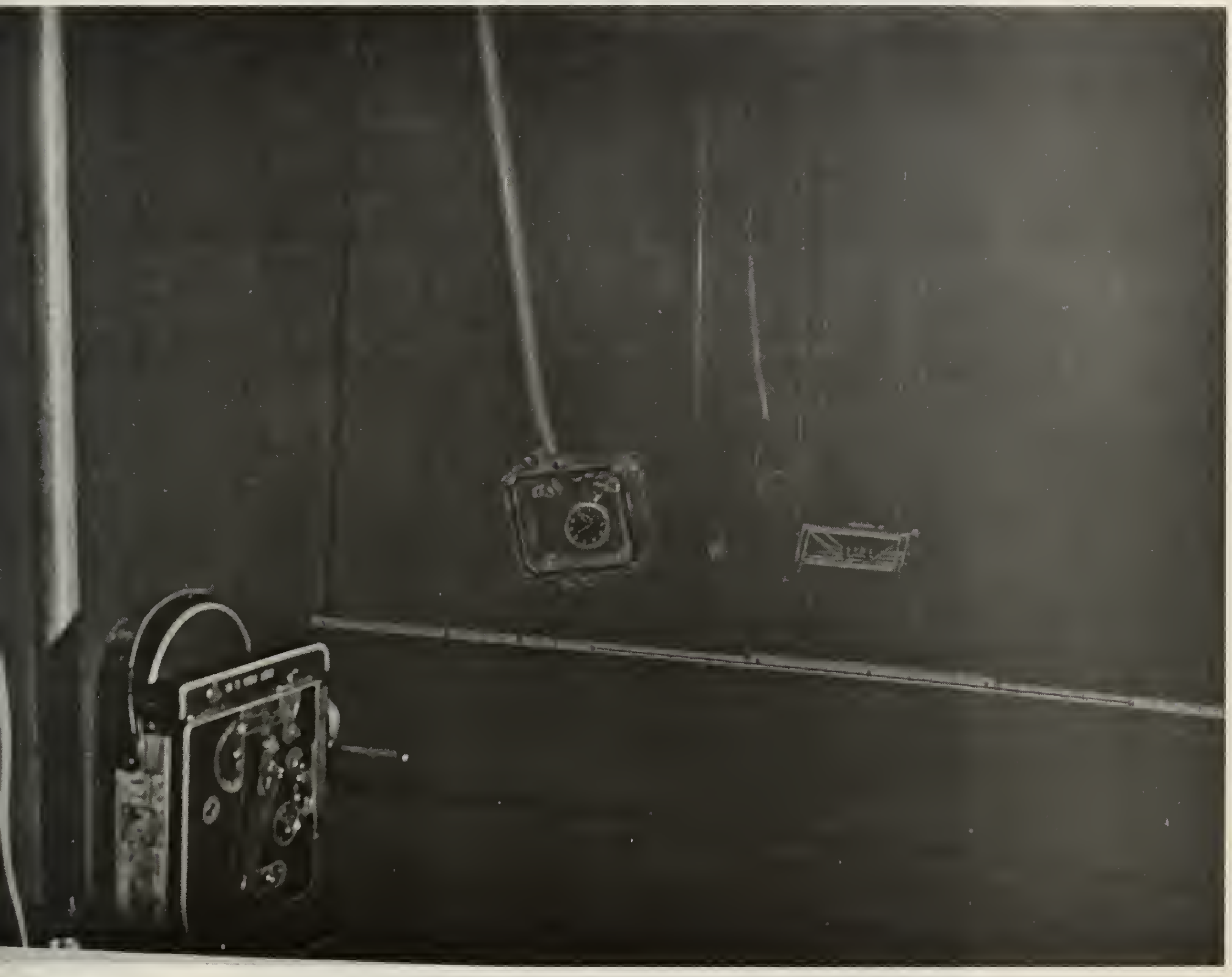
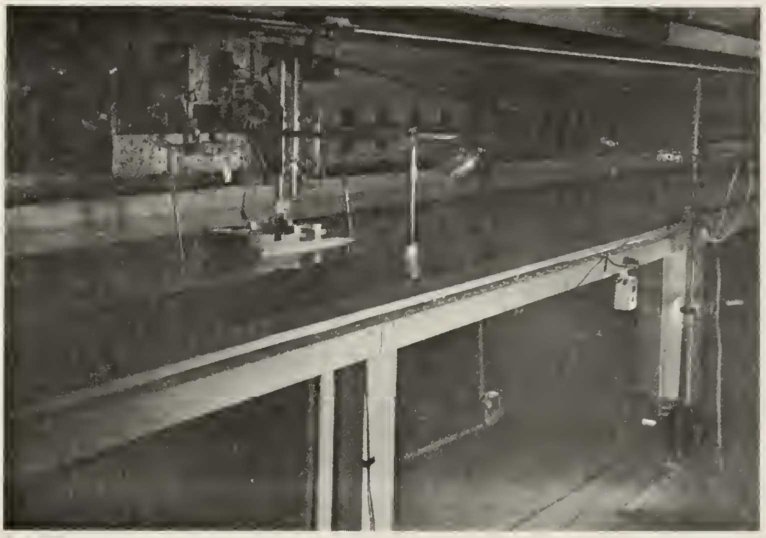
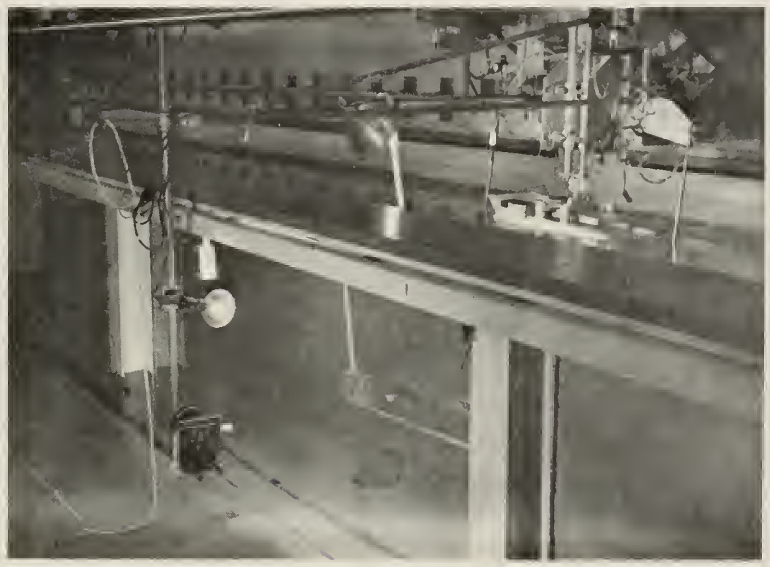


Figure 14. Data Taking Equipment Arrangement Showing Camera, Light, and Stopwatch in Foreground; Catamaran, Cradle, and Scale in Background.



A



B

Figure 15. Overall Equipment Arrangement at M.I.T. Tow Tank Showing a) Bow View, and b) Stern View.

for installation. A Bolex reflex 16mm motion picture camera, with a 100 foot film capacity was obtained from William Von Arx of Woods Hole Oceanographic Institution. Using a 15mm lens, Kodak 4x reversal film (ASA 320), and two photographic spot lights mounted on the aluminum frame for a camera setting of f5.6 at a speed of 16 fps, 600 feet of data were recorded under the skilful hand of photographic specialist Claude Ronne of the Woods Hole Oceanographic Institution. A representative sequence of cradle motion is included (Figure 16). The actual rolls of data are with Jim Mavor of W.H.O.I.

With model and recording devices complete, tests were conducted at the M.I.T. Tow Tank. The scope and results of those tests are discussed in the following section.

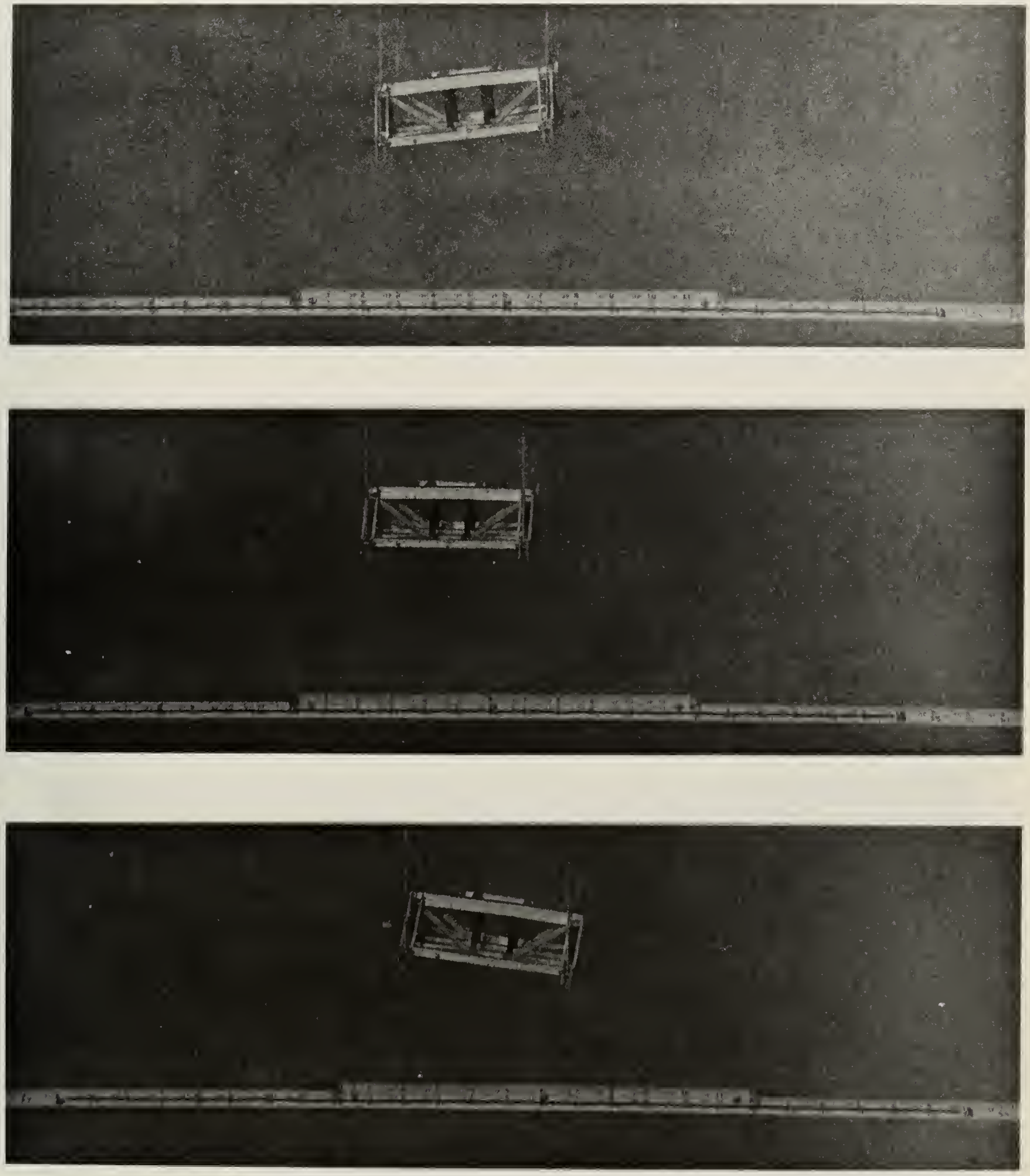
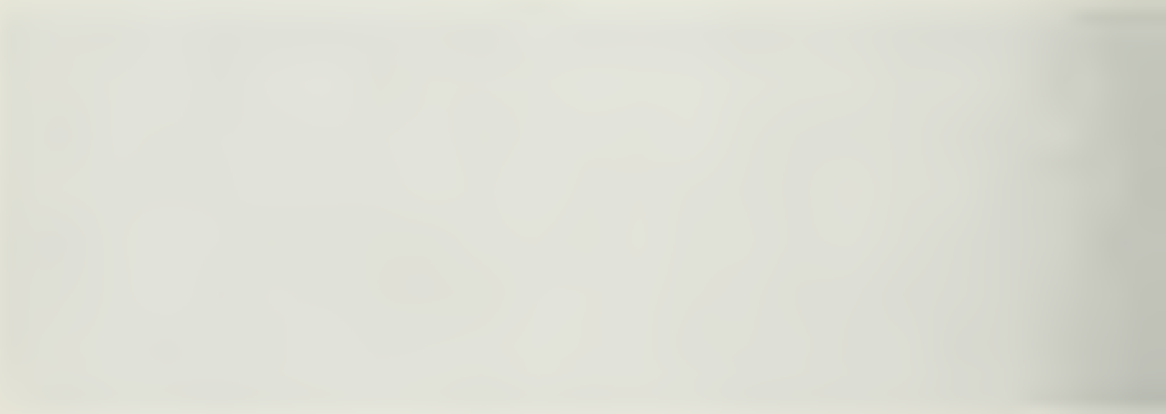


Figure 16. Representative Sequence of Cradle Motion (Catamaran Bow Pointing Left).



RESULTS

Eighty-one individual tow tank tests were conducted using the previously described 1/40 scale model of LULU, her chain, and cradle. Forty-two tests were conducted on the unmodified system such that the cradle was suspended 30 inches below LULU by means of four scale chains attached at each corner. Four tests were conducted on the unmodified system with the cradle suspended at a depth of 15 inches to investigate pendulum resonance. Twenty tests involved modification of the cradle by addition of a flat plate to the bottom of the cradle and the placement of springs at each corner between the chain and cradle support points (Figure 17). Fifteen tests were conducted using the modified cradle at a depth of 30 inches, but with a two point port and starboard spring suspension having an equivalent spring constant of one-fourth the four point spring system (Figure 18).

Figure 17. Model Cradle Showing Spring Detail.

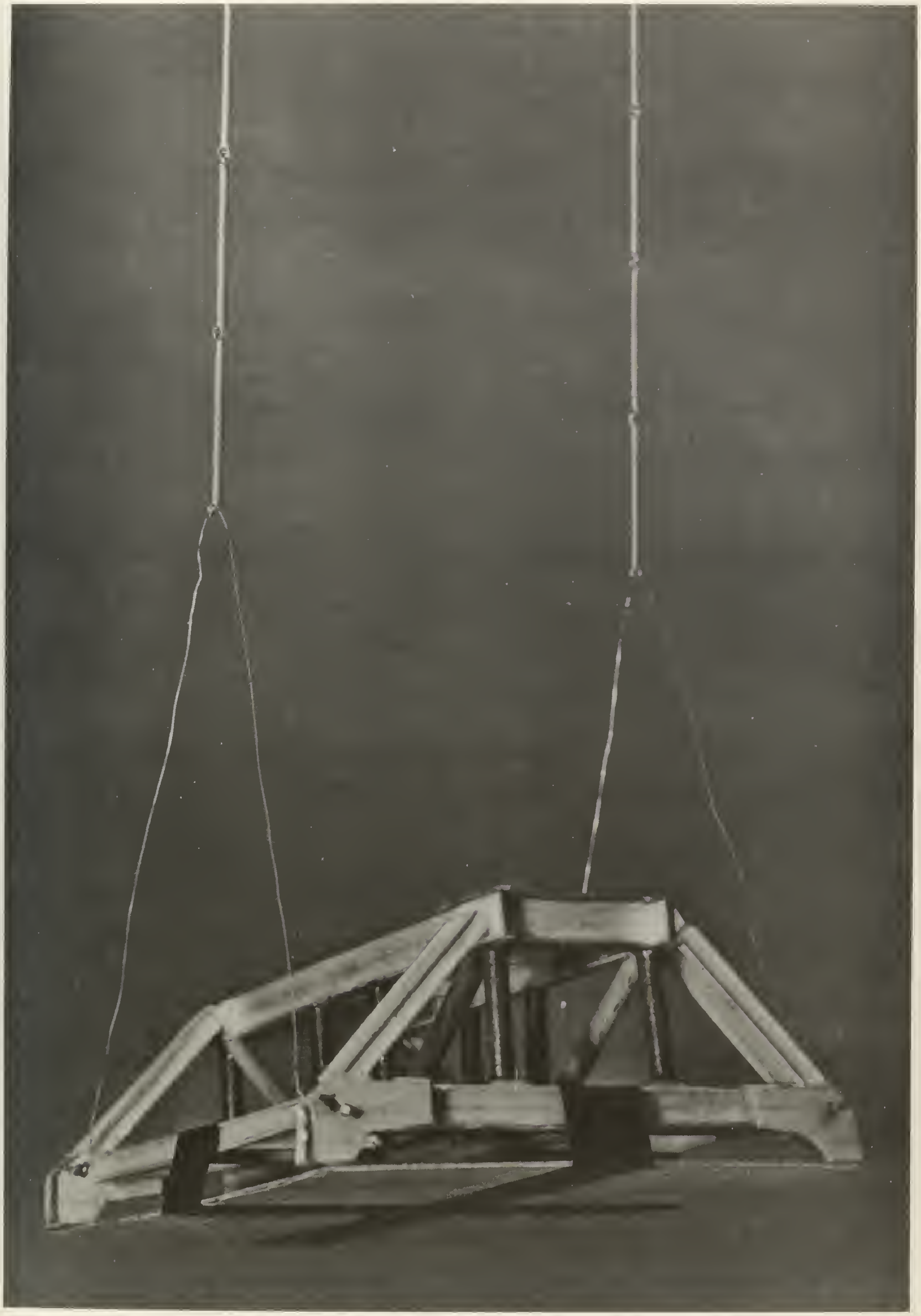


Figure 18. Model Cradle Alteration with Two Point Spring Suspension and Flat Plate.

As mentioned earlier, cradle motion response data consisting of 600 feet of 16mm film were recorded. The film was projected on a full scale grid by means of a time/motion study projector from which heave of the leading and trailing edges of the cradle, as well as pitch and trail angle were reduced. With the exception of trail angle (which is included here) the results are summarized in Appendix B. The run number refers to the code recorded on the film to designate the beginning of a test. Numbers 1 thru 46 represent the unaltered system (cradle suspended at 15 inches for runs 33, 34, 35, and 36). Runs 101 thru 120 are for a four point spring suspension, with flat plate attached to the cradle. Runs 121 thru 135 cover the two point spring suspension with flat plate as before (note that cradle pitch was insignificant).

The objective of this study was to determine the response of the recovery system in a state 4 sea, hence tests were conducted in regular waves at a full scale wave height of 8.5 feet. This represents the mean of the one tenth highest waves in a sea state 4, and scales to a tow tank wave height of 2.55 inches. Additionally, nearly all tests were run at a model wave height of 1 inch to check the linearity of systems response. Model wave lengths were set at 2, 4, 6, 8, and 10 feet in order to cover a range of λ/L ratios. In the unmodified tests, wave lengths of 7.75, 7.85, and 9.69 feet were also used to excite the suspended cradle (which appears as a viscous damped pendulum). The 7.75 foot wave length represents the half harmonic natural excitation frequency at zero model speed for a 30 inch pendulum. The 7.85

foot and 9.69 foot wave lengths represent the first harmonic natural excitation frequency for a 15 inch pendulum at model speeds of .207 and .498 knots respectively. Horizontal cradle displacement and surge oscillation information is summarized in Table III.

Table III

Summary of Horizontal Cradle Displacement and Cradle Surge Oscillation

MODEL SPEED (kts)	CRADLE DEPTH (inches)	HORIZONTAL[1] CRADLE DISPLACEMENT (inches)	CRADLE SURGE OSCILLATION (inches)
0.	30	0	.5
.207	30	3	.5
.207	15	1	.25
.498	30	10	1.0
.498	15	2	.25
.981	30	17	1.0
.498[2]	30	4.5	.25

1 measured from 0 speed position

2 modified cradle w/two point spring suspension and plate. (using after two chains of four point suspension)

Figures B1 thru B10 represent the pitch and heave response of the model and cradle as tested. Figures B1 and B2 indicate that: 1) the heave response of LULU increases with increasing forward speed, 2) the response is nearly linear for wave heights up to 8.5 feet, and 3) the model was tested at its resonant frequency which varies from 5 to 7 radians per second depending upon model speed. Figures B3 and B4 indicate that: 1) overall,

heave response of the trailing edge of the cradle increases with increasing forward speed to a maximum at .498 knots; however, at .981 knots the response is considerably reduced over the entire range of frequencies investigated: 2) the response is nearly linear for wave heights up to 8.5 feet with the exception of a 20 per cent difference at .207 knots, ω_e = 8 rad./sec., and a 40 per cent difference at .981 knots ω_e = 7 rad./sec.; and 3) resonance was observed between frequencies of 5 and 8 radians per second. Figures B5 and B6 indicate that: 1) catamaran pitch response tends to increase with increasing forward speed, 2) the response is nearly linear for wave heights up to 8.5 feet with the exception of a tuned phenomena at frequencies around 8 radians per second in the higher wave height experiments, and 3) resonance was observed between frequencies of 7 and 9 radians per second. Figures B7 and B8 indicate: 1) pitch response tends to decrease with increasing speed up to a speed of .498 knots for a model wave height of 1 inch, while increasing with speed for model wave height of 2.5 inches; 2) the response does not appear to be linear over the range of frequencies tested; and 3) for the smaller wave height, a distinct resonance appears at a frequency of about 5 radians per second, while resonance occurs from 7 to 10 radians per second for the larger wave height situation. Figure B9 shows that the four point spring suspension with added plate yields a significantly worse response in heave than the unmodified situation due to resonant reinforcement. Note that for a given speed, response decreases with increasing wave height

since viscous damping is amplitude dependent (Equation 6). The lower set of lines represents response of the two point suspension with added plate. The amplitude is significantly reduced for this range of frequencies; however, resonance has not been observed since it would occur at lower frequencies (longer wave lengths) than were investigated here. Figure B10 represents pitch response of the modified cradle, which as in heave, is significantly greater than the unmodified system. There was no pitch variation noted for the two point suspension; however, a constant down angle of 6 degrees was recorded when the cradle was towed at .498 knots. Figure 19 gives the reader an idea of the relative magnitude of wave height to ship response in a regular 8.5 foot wave. (Note bow and stern emergence, and rolling, breaking waves aft on the pontoon.)

No surge resonance was observed with the cradle at a depth of 15 inches. No yaw or sway instability was apparent up to tow speeds of .981 knots. With the exception of the four point spring suspension, the chain was not observed to go slack or kink. Cradle response overall was observed to be of greater magnitude (both pitch and heave) when the catamaran was lifting the cradle, than when the chains were eased, and the cradle fell of its own weight (indicating a no load condition at the lower end of the chain).

Cradle data for the two point suspension shown in Figure B10 has been replotted in Figure 20 along with curves representing solutions to Equation 9 for the following parameters:

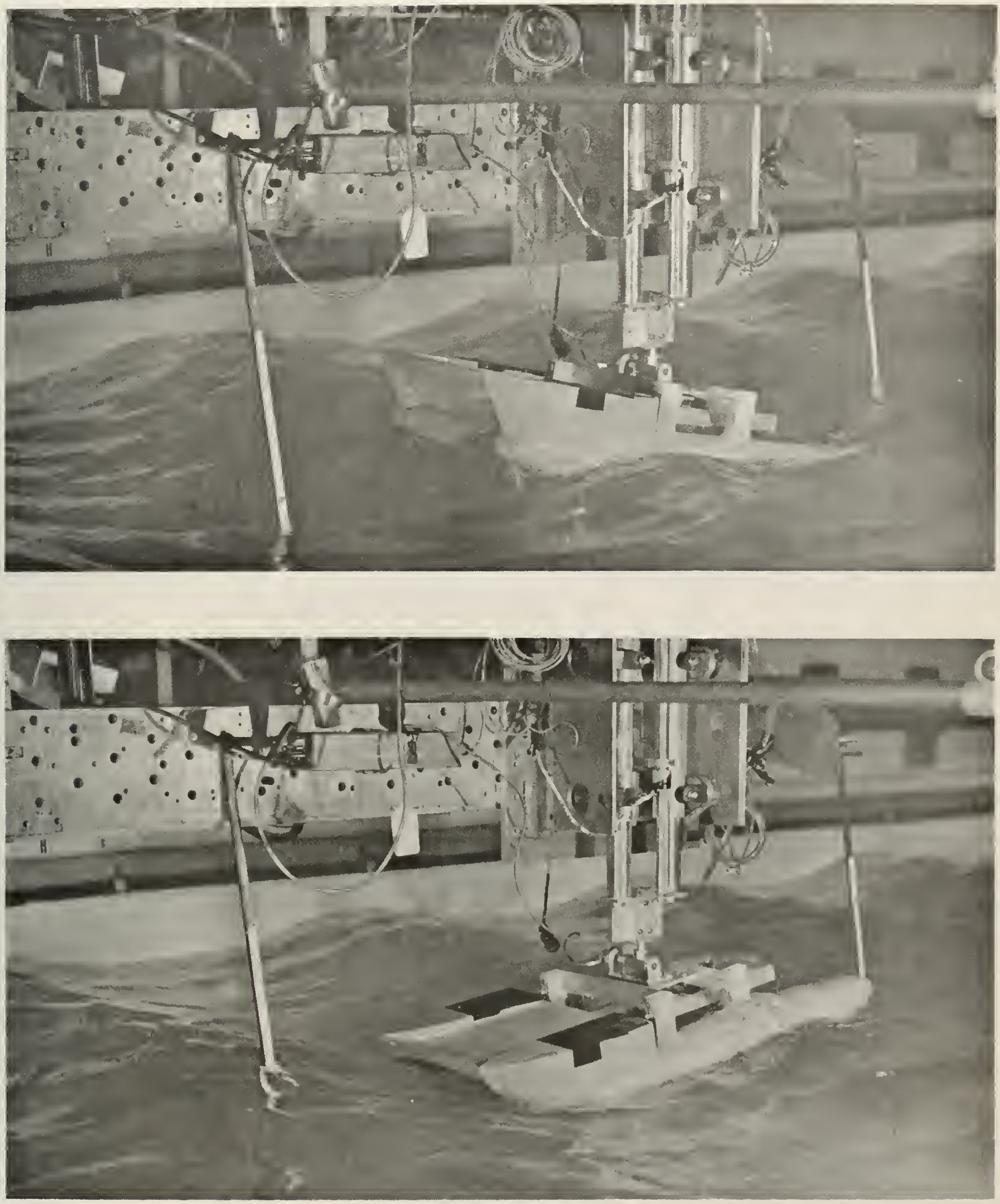


Figure 19. Catamaran Response in the Equivalent of 8.5 Foot High, 120 Foot Long Regular Waves Full Scale.

mass of cradle with plate (m): .01656 slugs

plate dimensions: 4.75" x 5.5"

added mass of cradle with plate:

$$m_a = \pi r^2 L\rho$$

$$= \frac{(3.14)(2.375)^2(5.5)(1.94)}{1728}$$

$$= .10936 \text{ slugs}$$

$M = m + m_a = .1259$ slugs

cradle damping with plate:

$$C = \frac{4\rho A_c C_d Y_o \omega}{3\pi}$$

$$= \frac{(4)(1.94)(4.75)(5.5)(1.16)}{(3)(3.14)(144)} y_o \omega$$

$$C = .1503 y_o \omega$$

equivalent spring constant (k): 1.24 lbs/ft

natural frequency:

$$\omega_n = (k/M)^{1/2}$$

$$= (1.24/.1259)^{1/2}$$

$$\omega_n = 3.138 \text{ rad./sec.}$$

hence:

$$\left(\frac{4\rho A_c C_d}{3\pi M}\right)\left(\frac{\omega}{\omega_n}\right)^4 y_o^4 + \left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 y_o - X_o^2 = 0$$

becomes:

$$.0142\omega^4 y_o^4 + (1-.102\omega^2)^2 y_o^2 - X_o^2 = 0$$

Curves a, b, and c represent values of X_o equal to 1 inch, 1.581 inch, and 2.5 inch respectively. Experimental and theoretical agreement is good.

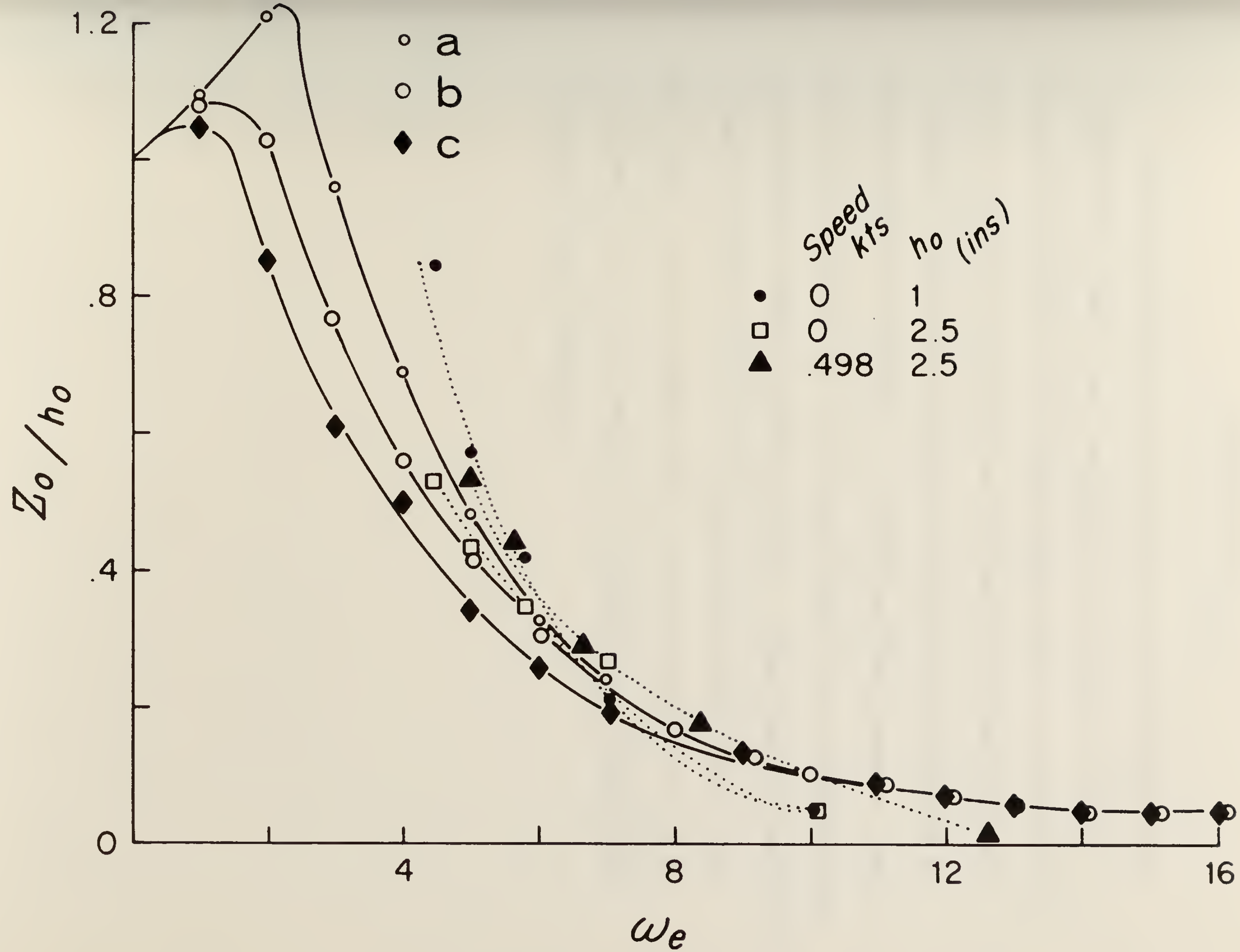


Figure 20. Plot of Theoretical and Actual Model Cradle Heave Response.

DISCUSSION OF RESULTS

The data presented in the previous section cover a wide range of ship speeds, wave heights, wave lengths, and basic passive alterations to the chain/cradle system. In almost all cases, a resonant condition was observed within the range of frequencies used in this study, so that the worst response to be expected was documented. As stated earlier (Hoerner, 1965) the drag coefficient for flat plates does not vary significantly for Reynolds' numbers greater than 100. Since cradle size/vertical velocity yielded a Reynolds' number on the order of 10^3, and full scale is on the order of 10^5, Froude scaling for size is valid and mdoel results should be considered to be applicable to the full scale situation.

CONCLUSIONS

Based upon the data obtained in this investigation, the following conclusions may be drawn.

1) As presently configured, cradle heave at a depth of 100 feet is only slightly attenuated over catamaran heave for forward speeds of less than 3 knots. Cradle heave is nearly half catamaran heave at 6 knots.

2) Cradle pitch response for the existing system is only slightly attenuated over catamaran response.

3) Full scale cradle heave in regular 8.5 foot waves would fall somewhere between 1 foot for high ship speeds, and wave lengths shorter than ship length, and 9 feet for slower ship speeds and wave lengths three or more times ship length.

4) Cradle pitch will vary from less than one degree to more than 20 degrees for the unaltered system.

5) It is possible to alter cradle response significantly (for better or worse) in both heave and pitch by changing the spring constant of the hoist, and by changing the added mass of the cradle.

6) It is possible by various means already discussed (i.e.

cradle weight reduction, venetian blind plate, jettisonable drogue, roller springs) to drive the natural frequency of the cradle low enough, so that response in sea state 4 is well below half the response of the catamaran in heave.

7) It is possible to completely decouple catamaran pitch from cradle motion by reducing the four point suspension from the ship to a two point port and starboard arrangement.

8) By converting to a two point ship suspension, and moving the chain support point horizontally along LULU to the point of minimum heave, cradle heave would be reduced over present response.

In summary, as presently configured this system does not look any more attractive than the present surface recovery mode.

RECOMMENDATIONS

A simple full scale calm water experimental measurement of the trail angle of the cradle suspended at 100 feet at a given speed would provide a point of calibration for model tests. If the trail angle is greater in real life than as modeled, the drag of the model is proportionally less, and the response of the cradle in full scale can be expected to be less than was observed in this study. Conversely, a smaller angle would suggest greater model drag than full scale, and hence greater full scale response due to the reduced viscous damping.

Experiments should be carried out in the tow tank using programmed sea spectra to duplicate real life random seas. Additionally, a 1/40 scale model of ALVIN should be introduced in the vicinity of the lowered cradle to study any interface effects. Once this has been accomplished, dynamics of the cradle/ALVIN recovery as the chain is reeled in through the air-sea interface should be investigated.

Although the two point spring suspension using added mass effects appears quite feasible, more model tests are required. Cradle models of various size, buoyancy, and shape must be tested, as well as a much wider range of spring constants and possibly other devices and configurations.

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APPENDIX

A. Data used in model radius of gyration calculations

B. Data/graphical presentation

APPENDIX A

Data Used in Model Radius of
Cyration Calculations

Catamaran Item Designation	Weight (Long Tons)	Distance From Mid-Ships Section (Ft.) (+ Forward)
Tank 2S	2.98	+27
Tank 3S (FWD)	5.16	+5
FWD Arch	15	+33
FWD Engine	7.5	+33
FWD Hulls	2.1 tons/ft.	+0 - 47.75
FWD Deck	1.36 tons/ft.	+11 - 47.75
Tank 3S (aft.)	4.14	3.75
Tank 4S	9.3	-15
Tank 5S	11.2	-31
Tank 4P	7.73	-15
Tank 5P	9.2	-15
Aft. Arch	17	-33
Deckhouse	5	-33
Aft. Hulls	2.1 tons/ft.	-0 - 47.75
Aft. Engine (2)	15	-45
Fuel Aft. Arch	16.9	-33
Misc. Aft.	1.05 tons/ft.	-0 - 47.75

APPENDIX B

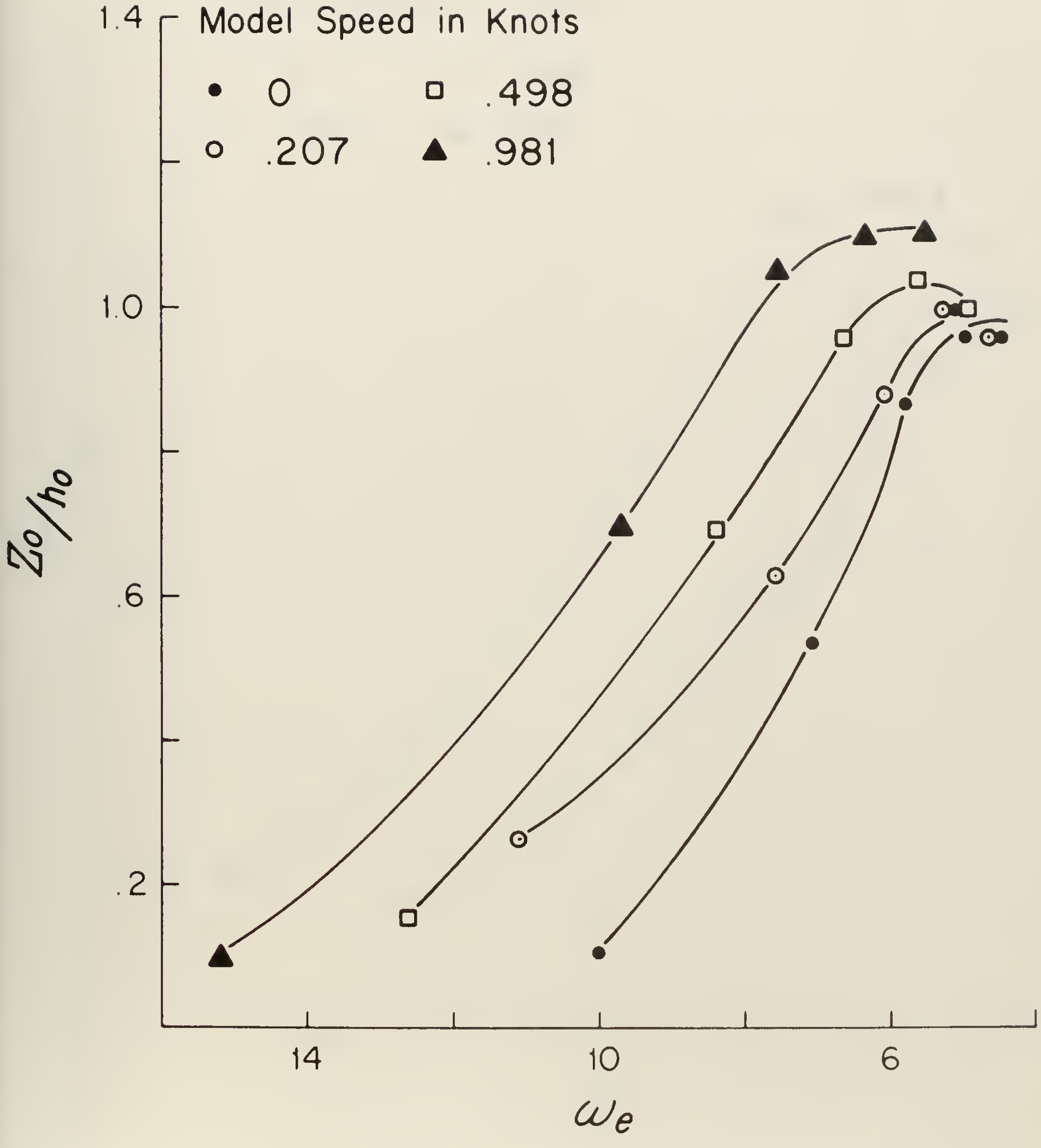

Figure B1. Catamaran Heave Response (h_o = 1").

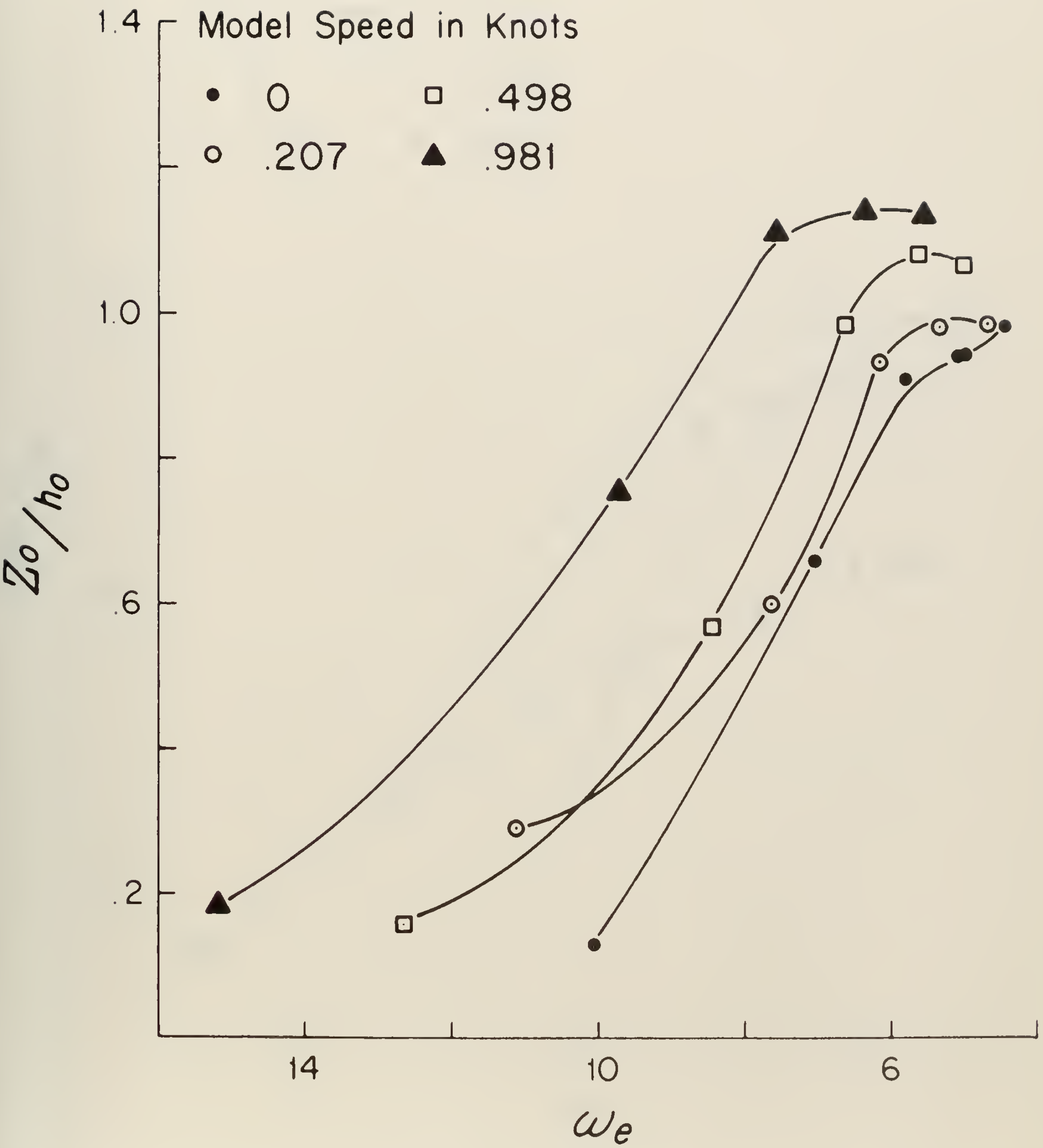

Figure B2. Catamaran Heave Response (h_o = 2.5").

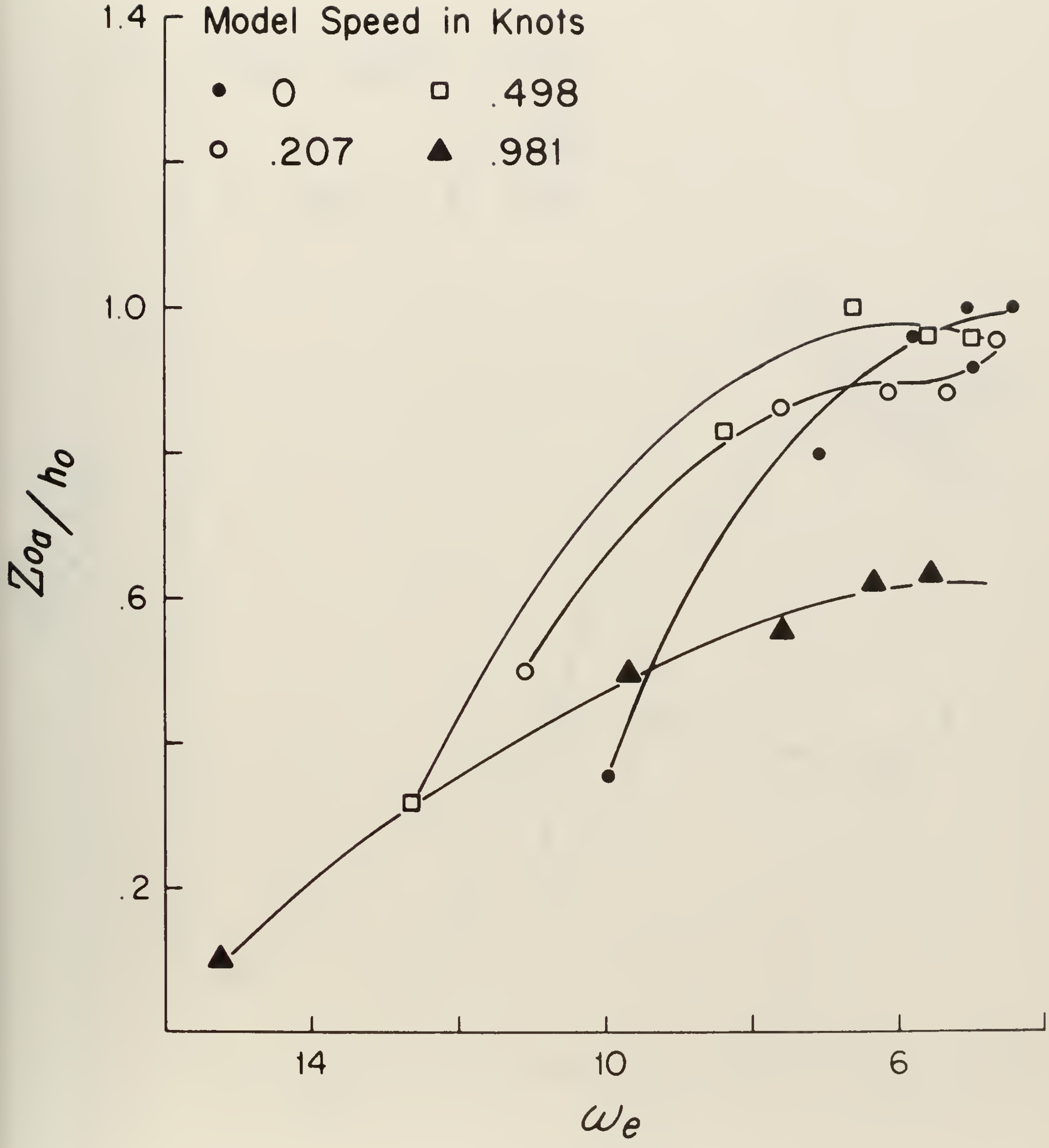

Figure B3. Cradle Heave Response ($h_o = 1''$).

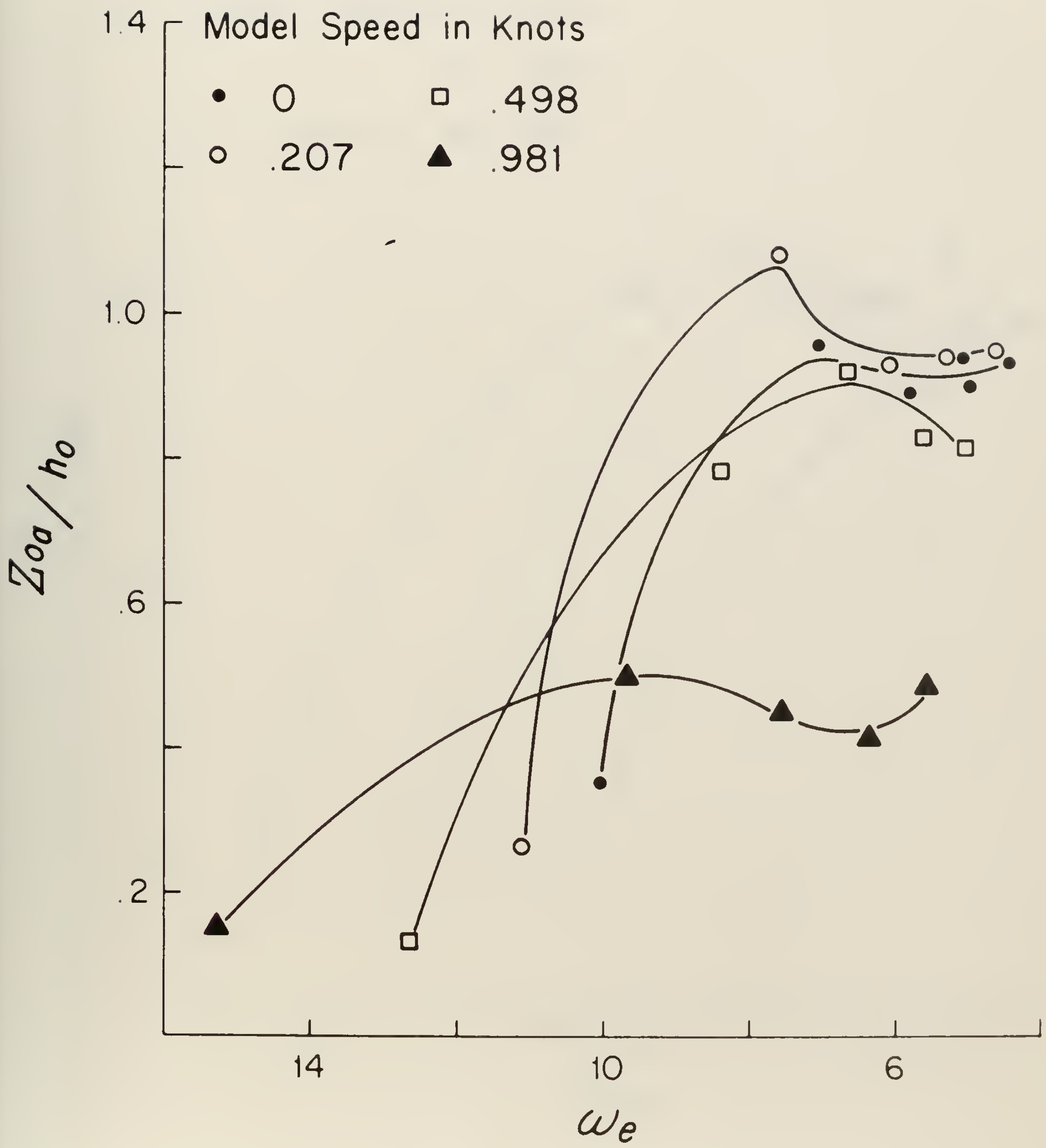

Figure B4. Cradle Heave Response (h_o = 2.5").

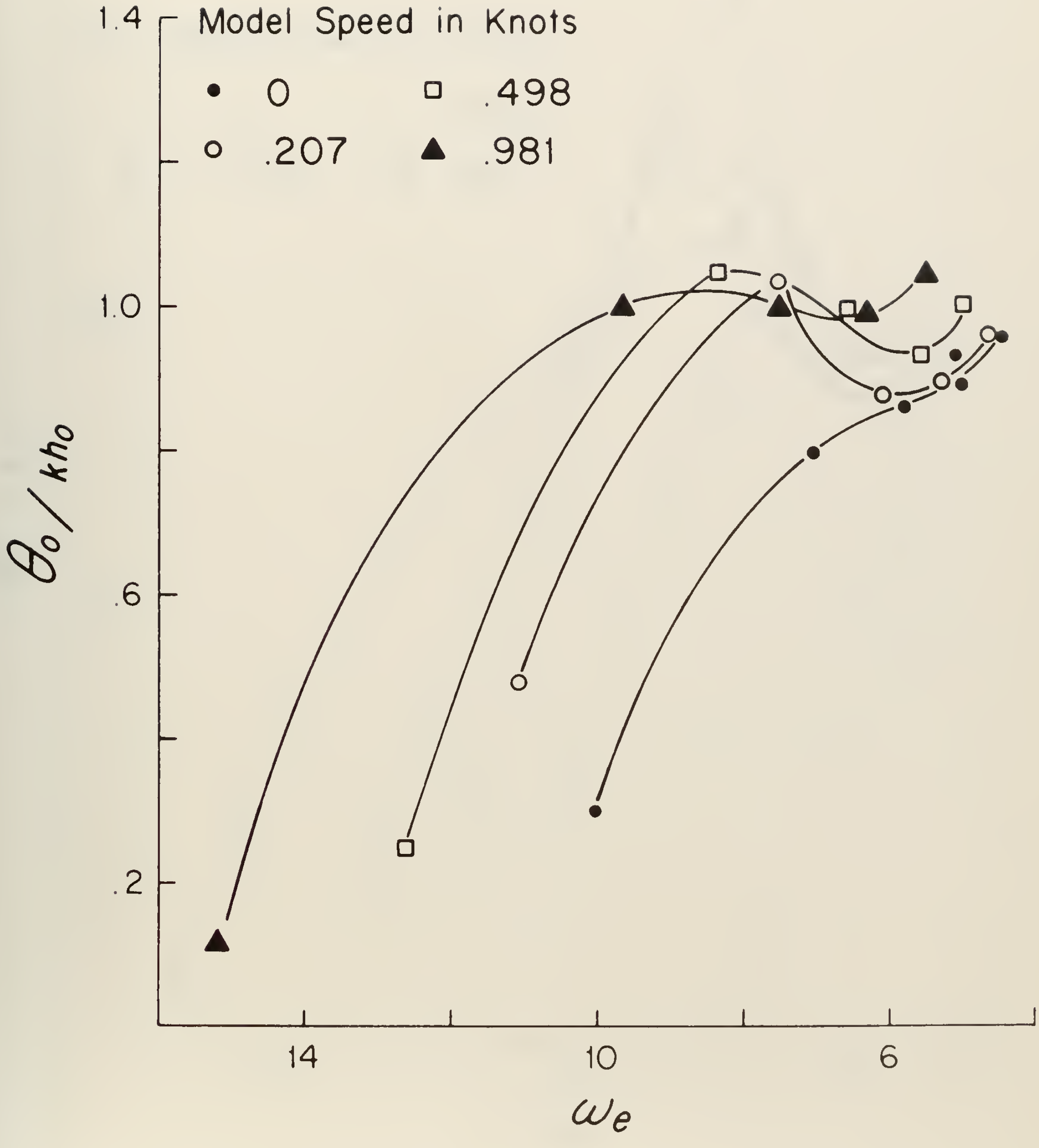

Figure B5. Catamaran Pitch Response (h_o= 1").

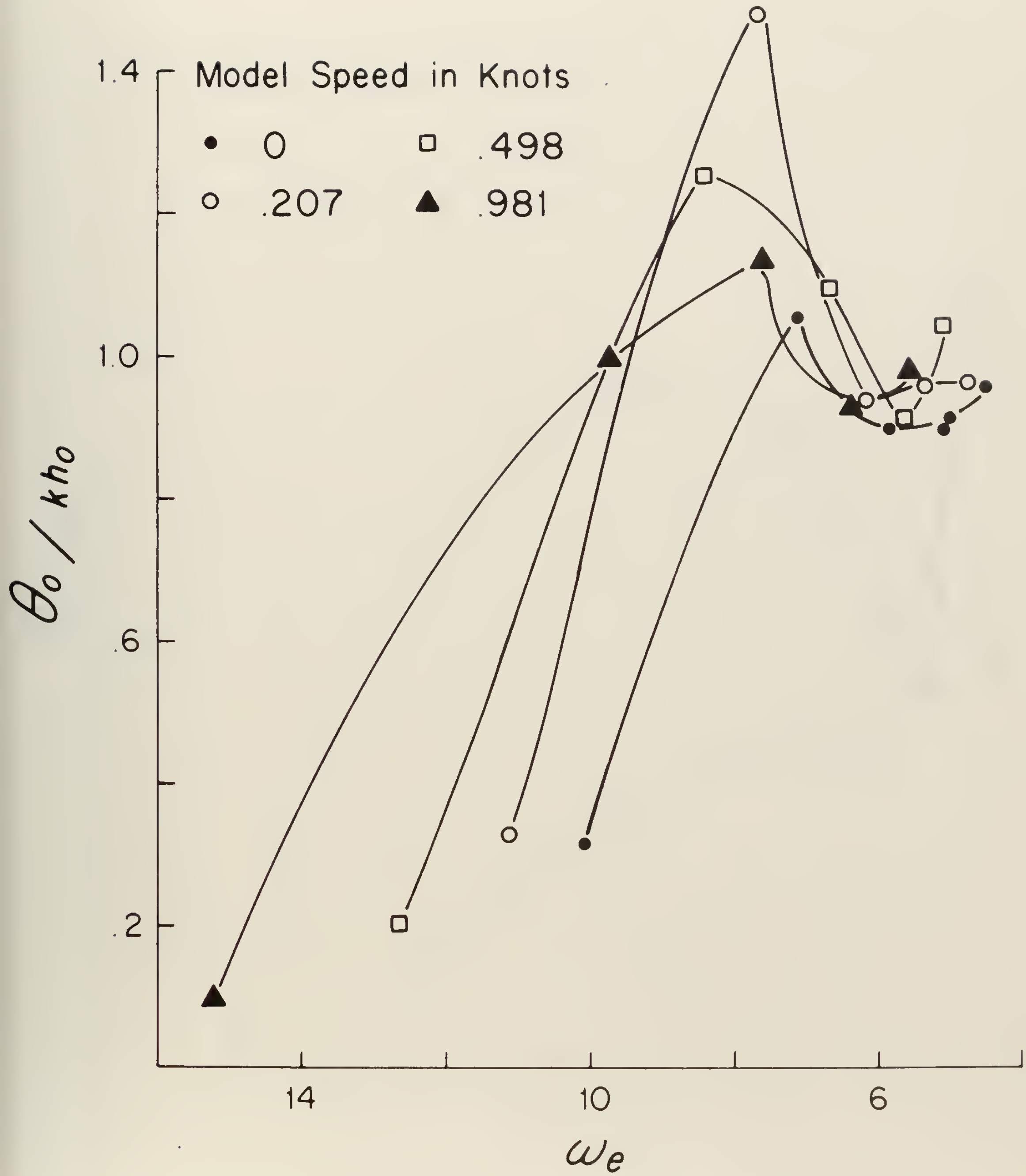

Figure B6. Catamaran Pitch Response ($h_o = 2.5''$).

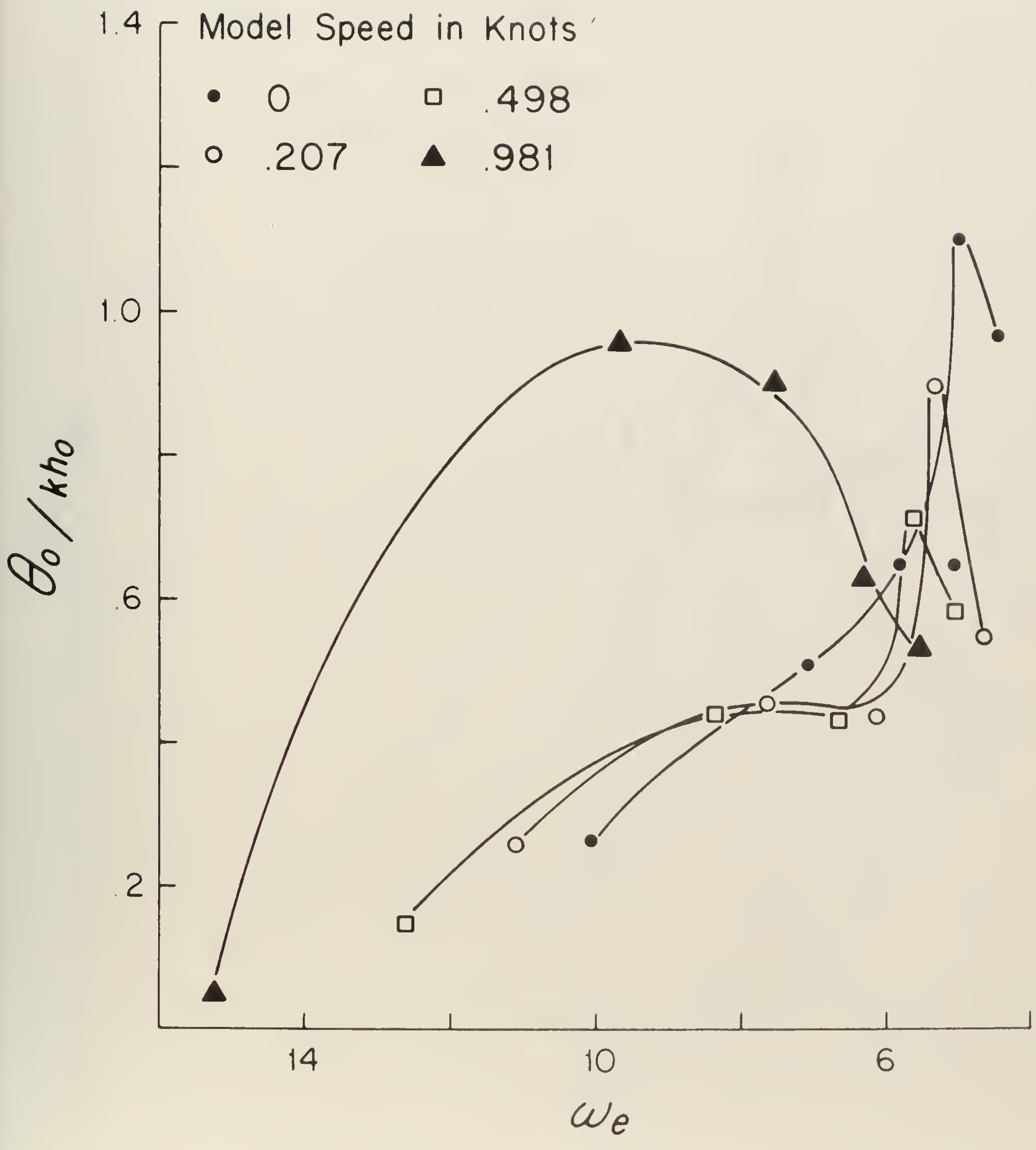

Figure B7. Cradle Pitch Response (h_o= 1").

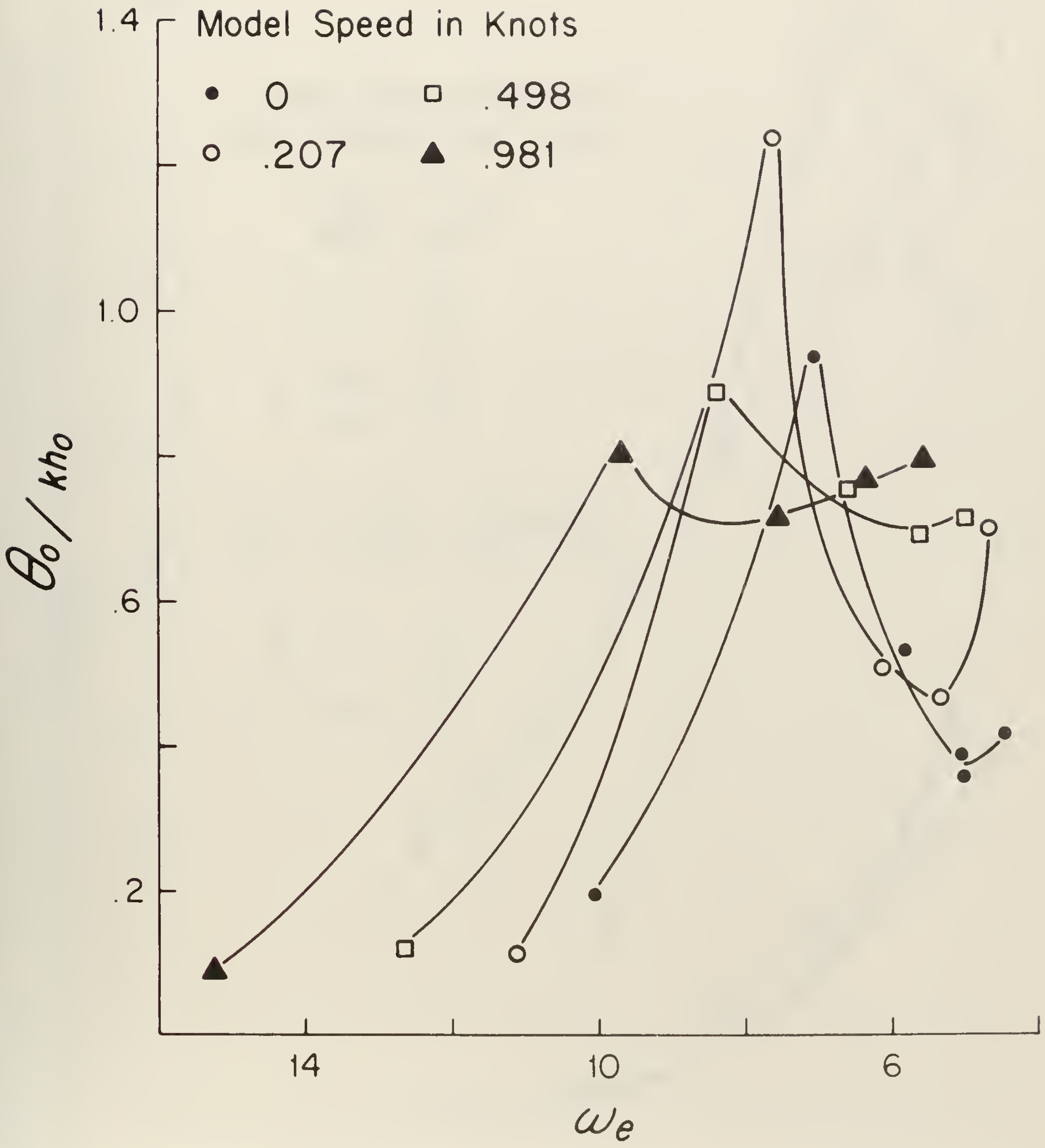

Figure B8. Cradle Pitch Response (h_o = 2.5").

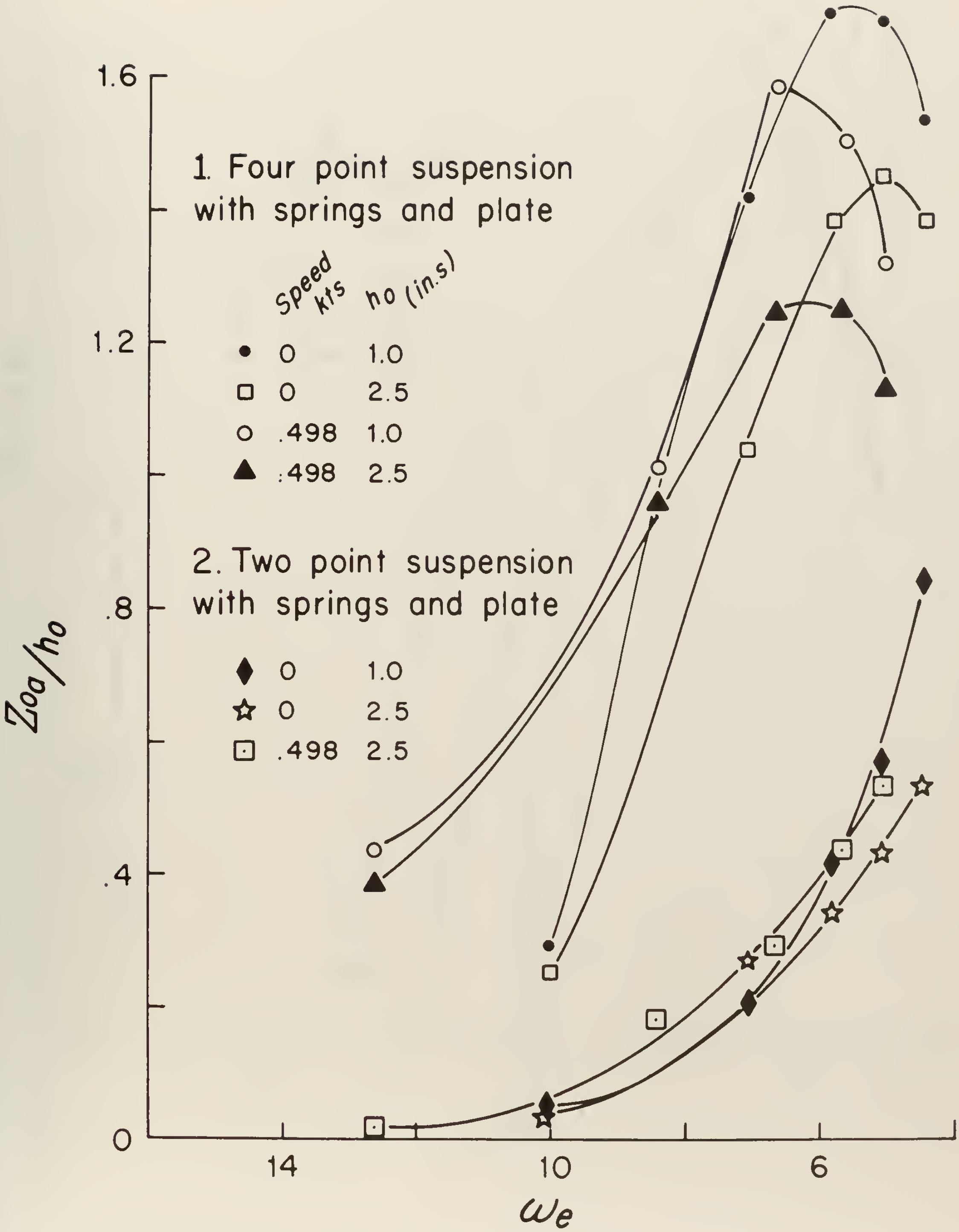

Figure B9. Modified Cradle Heave Response.

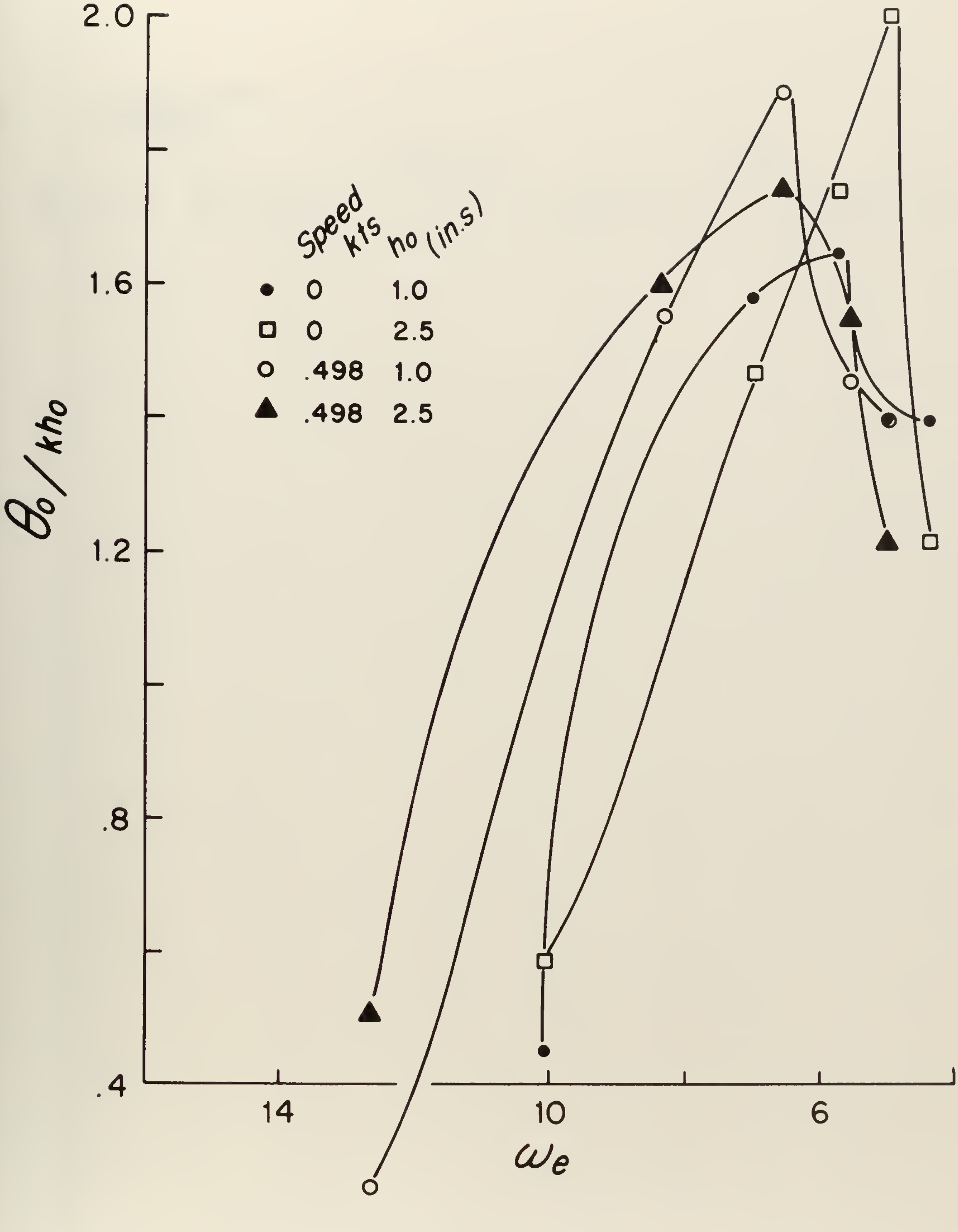

Figure B10. Modified Cradle Pitch Response.

Summary of Data

1 Measured at Midships
2 Leading Edge
3 Trailing Edge
4 $K = \frac{2\pi}{\lambda}$

RUN NO.	λ (ft)	h_o (in)	u_m (kts)	ω_e (rad/sec)	CATAMARAN z_o[1] (in)	z_o/h_o	θ (deg)	θ/Kh_o[4]	CRADLE z_{of}[2] (in)	z_{oa}[3] (in)	z_{of}/h_o	z_{oa}/h_o	θ (deg)	θ/Kh_o[4]
1	2	1.1	0	10.04	.12	.11	5.0	.30	.1	.4	.09	.36	4.5	.27
2	4	1.25	0	7.10	.66	.53	7.5	.80	.65	1.0	.52	.80	4.75	.51
3	6	1.15	0	5.80	1.00	.87	5.0	.87	1.0	1.1	.87	.96	3.75	.65
4	7.75	1.1	0	5.10	1.10	1.00	4.0	.94	1.0	1.1	.91	1.0	2.75	.65
5	8	1.2	0	5.02	1.15	.96	4.0	.89	1.0	1.1	.83	.92	5.0	1.11
6	10	1.2	0	4.49	1.15	.96	3.5	.97	1.05	1.2	.88	1.0	3.5	.97
7	2	1.1	.207	11.13	.30	.27	8.0	.48	.55	.55	.50	.5	4.25	.26
8	4	1.15	.207	7.64	.72	.63	9.0	1.04	.55	1.0	.49	.87	4.0	.46
9	6	1.25	.207	6.16	1.10	.88	5.5	.88	.85	1.1	.68	.88	2.75	.44
10	8	1.25	.207	5.29	1.25	1.00	4.25	.90	1.0	1.1	.80	.88	4.25	.90
11	10	1.2	.207	4.71	1.15	.96	3.5	.97	1.1	1.15	.92	.96	2.0	.55
12	2	1.25	.498	12.68	.2	.16	4.75	.25	.2	.4	.16	.32	2.75	.15
13	4	1.2	.498	8.42	.84	.70	9.5	1.05	.65	1.0	.54	.83	4.0	.44
14	6	1.15	.498	6.68	1.1	.96	5.75	1.00	.85	1.15	.74	1.0	2.5	.43
15	8	1.2	.498	5.68	1.25	1.04	4.25	.94	1.05	1.15	.88	.96	3.25	.72
16	10	1.15	.498	5.02	1.15	1.0	3.5	1.01	.9	1.1	.78	.96	2.0	.58
17	2	1.55	0	10.04	.2	.13	7.5	.32	.1	.55	.06	.35	4.5	.19
18	4	2.75	0	7.10	1.8	.66	22.0	1.06	1.6	2.66	.58	.96	19.25	.93
19	6	2.65	0	5.80	2.4	.91	12.0	.90	2.1	2.35	.79	.89	7.0	.53
20	7.75	2.65	0	5.10	2.5	.94	9.25	.90	2.3	2.5	.87	.94	4.0	.39
21	8	2.6	0	5.02	2.45	.94	9.0	.92	2.2	2.35	.85	.90	3.5	.36
22	10	2.75	0	4.49	2.7	.98	8.0	.97	2.45	2.55	.89	.93	3.5	.42
23	2	1.7	.207	11.13	.5	.29	8.5	.33	.4	.45	.24	.27	2.75	.11
24	4	2.6	.207	7.64	1.55	.60	29.0	1.48	1.3	2.8	.50	1.08	24.0	1.23

Summary of Data

1 Measured at Midships
2 Leading Edge
3 Trailing Edge
4 $K = \frac{2\pi}{\lambda}$

					CATAMARAN				CRADLE					
RUN NO.	λ (ft)	h_o (in)	u_m (kts)	ω_e (rad/sec)	z_o^1 (in)	z_o/h_o	θ (deg)	β^4/Kh_o	$z_{o_f}^2$ (in)	$z_{o_a}^3$ (in)	z_{o_f}/h_o	z_{o_a}/h_o	β (deg)	β^4/Kh_o
25	6	2.65	.207	6.16	2.45	.93	12.5	.94	2.05	2.45	.78	.93	6.75	.51
26	8	2.55	.207	5.29	2.5	.98	9.25	.97	2.2	2.4	.86	.94	4.5	.47
27	10	2.75	.207	4.71	2.7	.98	8.0	.97	2.45	2.6	.89	.95	5.75	.70
28	2	1.5	.498	12.68	.24	.16	4.75	.21	.2	.2	.13	.13	2.75	.12
29	4	2.7	.498	8.42	1.55	.57	25.5	1.26	1.25	2.1	.46	.78	18.0	.89
30	6	2.55	.498	6.68	2.5	.98	14.0	1.10	1.85	2.35	.73	.92	9.75	.76
31	8	2.6	.498	5.68	2.8	1.08	9.0	.92	1.85	2.15	.71	.83	6.75	.69
32	10	2.7	.498	5.02	2.9	1.07	8.5	1.05	2.05	2.2	.76	.82	5.75	.71
33	7.85	1.2	.207	5.35	1.15	.96	4.25	.93	.95	1.05	.79	.88	3.25	.71
34	9.69	1.15	.498	5.12	1.2	1.04	3.5	.98	.95	1.1	.83	.96	3.5	.98
35	7.85	2.6	.207	5.35	2.5	.96	9.25	.93	2.1	2.35	.81	.91	5.5	.55
36	9.69	2.75	.498	5.12	2.9	1.05	9.0	1.06	2.15	2.5	.78	.91	6.25	.73
37	2	1.0	.981	15.24	.1	.1	1.75	.12	.15	.1	.15	.1	.75	.05
38	4	1.0	.981	9.70	.7	.7	7.5	1.00	.85	.5	.85	.5	7.25	.96
39	6	1.0	.981	7.53	1.05	1.05	5.0	1.00	.35	.55	.35	.55	4.5	.90
40	8	1.05	.981	6.32	1.15	1.10	3.75	.95	.4	.65	.38	.62	2.5	.63
41	10	.95	.981	5.53	1.05	1.11	3.0	1.05	.45	.6	.47	.63	1.5	.53
42	2	1.3	.981	15.24	.23	.18	2.0	.10	.2	.2	.15	.15	1.75	.09
43	4	2.0	.981	9.70	1.5	.75	15.0	1.00	.85	1.0	.43	.5	12.0	.80
44	6	2.1	.981	7.53	2.3	1.11	12.0	1.14	.9	.95	.43	.45	7.5	.71
45	8	2.15	.981	6.32	2.45	1.14	7.5	.93	.9	1.1	.42	.51	6.25	.77
46	10	2.2	.981	5.53	2.5	1.14	6.5	.98	1.05	1.4	.48	.64	5.25	.79
101	2	1.05	0	10.04	.13	.12	4.25	.27	.5	.3	.48	.29	7.25	.46
102	4	.95	0	7.10	.46	.48	6.75	.95	.65	1.35	.68	1.42	11.25	1.58
103	6	1.0	0	5.80	.9	.9	4.75	.95	1.3	1.7	1.3	1.7	8.25	1.65
104	8	.95	0	5.02	1.05	1.11	3.75	1.05	1.35	1.6	1.42	1.68	5.0	1.40
105	10	.95	0	4.49	1.1	1.16	3.0	1.05	1.3	1.45	1.37	1.53	4.0	1.40
106	2	1.6	0	10.04	.24	.15	7.25	.30	.8	.4	.5	.25	14.25	.59

Summary of Data

1 Measured at Midships
2 Leading Edge
3 Trailing Edge
4 $K = \frac{2\pi}{\lambda}$

					CATAMARAN				CRADLE					
RUN NO.	λ (ft)	h_o (in)	u_m (kts)	ω_e (rad/sec)	z_o^1 (in)	z_o/h_o	θ (deg)	θ/Kh_o [4]	z_{of}^2 (in)	z_{oa}^3 (in)	z_{of}/h_o	z_{oa}/h_o	θ (deg)	θ/Kh_o [4]
107	4	2.35	0	7.10	1.3	.55	15.05	.85	.35	2.45	.15	1.04	26.0	1.47
108	6	2.35	0	5.80	2.0	.85	10.1	.86	1.85	3.25	.79	1.38	20.5	1.74
109	8	2.35	0	5.02	2.2	.94	8.5	.96	2.35	3.4	1.0	1.45	17.75	2.01
110	10	2.6	0	4.49	2.65	1.02	7.5	.96	3.0	3.6	1.15	1.38	9.5	1.22
111	2	.8	.498	12.68	.34	.43	3.75	.31	.3	.35	.38	.44	3.0	.25
112	4	1.05	.498	8.42	.6	.57	7.55	.96	.25	1.2	.24	1.14	12.25	1.55
113	6	.95	.498	6.68	.95	1.0	5.5	1.16	.85	1.5	.89	1.58	9.0	1.89
114	8	1.0	.498	5.68	1.1	1.1	4.0	1.06	1.05	1.5	1.05	1.5	5.5	1.46
115	10	.95	.498	5.02	1.05	1.11	3.1	1.09	1.1	1.25	1.16	1.32	4.0	1.40
116	2	1.2	.498	12.68	.3	.25	5.0	.28	.45	.45	.38	.38	9.25	.51
117	4	2.5	.498	8.42	1.4	.56	22.0	1.17	.3	2.4	.12	.96	30.0	1.60
118	6	2.45	.498	6.68	2.3	.94	13.5	1.10	1.55	3.05	.63	1.24	21.5	1.75
119	8	2.4	.498	5.68	2.6	1.08	9.0	1.00	2.1	3.0	.88	1.25	14.0	1.55
120	10	2.65	.498	5.02	2.65	1.0	8.0	1.01	2.35	3.0	.89	1.13	9.75	1.22
121	2	1.0	0	10.04	.3	.3	4.0	.27	-	.05	-	.05	-	-
122	4	.95	0	7.10	.6	.63	5.5	.77	-	.2	-	.21	-	-
123	6	.95	0	5.80	.9	.95	4.25	.89	-	.4	-	.42	-	-
124	8	1.05	0	5.02	1.0	.95	3.5	.89	-	.6	-	.57	-	-
125	10	.95	0	4.49	1.1	1.16	2.75	.97	-	.8	-	.84	-	-
126	2	1.25	0	10.04	.25	.2	6.75	.36	-	.05	-	.04	-	-
127	4	2.25	0	7.10	1.55	.69	15.5	.92	-	.6	-	.27	-	-
128	6	2.35	0	5.80	2.3	.98	10.5	.89	-	.8	-	.34	-	-
129	8	2.35	0	5.02	2.25	.96	8.0	.91	-	1.0	-	.43	-	-
130	10	2.55	0	4.49	2.6	1.02	7.25	.95	-	1.35	-	.53	-	-
131	2	2.35	.498	12.68	.6	.26	4.5	.13	-	.05	-	.02	-	-
132	4	2.2	.498	8.42	1.4	.64	21.5	1.30	-	.4	-	.18	-	-
133	6	2.4	.498	6.68	2.35	.98	11.5	.96	-	.7	-	.29	-	-
134	8	2.45	.498	5.68	2.45	1.0	8.25	.90	-	1.05	-	.43	-	-
135	10	2.65	.498	5.02	2.7	1.02	8.0	1.01	-	1.4	-	.53	-	-

Thesis 135479
C53078 Cohen
An experimental analysis of the dynamics of a submerged tethered cradle in a seaway.